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Methods for Evaluating Flammability Characteristics of Shipboard Materials

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A critical review of small-scale flammability tests methods for characterizing the fire performance of materials is presented. An approach is given for developing performance criteria and for controlling the flammability of shipboard materials based on the required full-scale performance. Modern flammability tests provide data which has been demonstrated over a range of applications to provide predictions of full-scale performance. This correlation between small-scale and real-scale performance is accomplished with a combination of empirical correlations, theoretical calculations, and computer-based modeling. The ability to correlate small-scale testing and real-scale performance is relatively recent and follows developments in small-scale testing and modeling. None of the current Navy specifications provide these data, and hence, it is not possible to quantify the benefit of modified or improved materials. In order to provide realistic assessment of current materials and possible shipboard passive fire safety improvements, performance improvements must be quantifiable and related to shipboard requirements. This study proposes methods to accomplish the relationship between material flammability specifications and shipboard performance.

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1.0 INTRODUCTION

The purpose of this report is to review the U.S. Navy passive fire protection program and provide guidance on the near and long-term future direction of this program. This report was prepared as part of a Naval Sea Systems Command task entitled, "Passive Fire Protection Materials Requirements Analysis," which included the following tasks.

Task 1 — Collect, summarize, and evaluate all current passive fire protection requirements, relative to relevance, expected full-scale performance, and current state of fire testing technology. Summarize existing and near term fire testing protocols and methods.

Task 2 — Review existing documentation of fire performance objectives. Review fire loss statistics, threat analyses (combat and self-inflicted). Identify key performance areas (fire growth, ignition, flame spread, toxicity, smoke, fire resistance, etc.). Develop a qualitative set of fire protection objectives.

Task 3 — Evaluate current and proposed state-of-the-art fire testing protocols relative to their performance in estimating full-scale behavior and their ability to be used to attain quantitative fire protection goals.

Task 4 — Identify and review, relative to availability and validity, the scaling relationships necessary to derive full-scale behavior estimates from small-scale results. Identify important material parameter (performance) groups that relate small-scale to expected end use performance. Identify gaps in necessary techniques. Evaluate near and long term efficacy and required development, if any.

This report deals with findings of these tasks with some treatment of near-term research and development requirements.

One of the primary goals of this project is to provide a method which will allow a more quantitative analysis of the benefits associated with making future material improvements and the risks of not doing so. A benefit of this approach is that is will assist the integration of fire threats into more general ship survivability models, where again the benefits of improved flammability materials can be measured.

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This report does not address in detail how to treat specific applications, e.g., packaging, cables, mattresses, draperies, deck coverings, etc. It outlines an approach, demonstrates how this approach has been applied to other specific applications, and proposes near-term development needs based on specific Navy requirements.

1.1 Overview

This effort is partially directed at providing a more quantitative basis for decision making relative to passive fire protection requirements. It involves a combination of probabalistic, deterministic, and economic variables which are integrated into a framework involving risk analysis, deterministic modeling, and small-, moderate-, and large-scale testing. It may be useful to describe a pro forma example as an illustration of what the remainder of this report attempts to describe.

Assume, as a result of fire loss experience or a risk analysis, that a particular material/application has been identified for improvement. For purposes of this example, mattresses will be used. The traditional approach (Navy and non-Navy) would be to do the following:

1. select candidate improved materials,
2. perform small-scale testing (ignition, smoke, flame spread),
3. conduct full-scale compartment test,
4. ensure that the candidate material met all other application requirements,
5. evaluate full-scale tests in terms of "best" performing material, and
6. prepare specifications based on small-scale tests.

There are significant limitations to this approach primarily driven by problems with the state-of-the-art in small- (and full-) scale testing. These limitations include the following:

1. There is generally no connection between the small-scale tests and full-scale performance;
2. The full-scale test results cannot be generalized to other compartments, ignition scenarios, threat levels, etc. Hence, the behavior of the material in other scenarios cannot be evaluated,
3. The benefit(s) of improving the material cannot be quantitatively judged;
4. There is no performance objective related to higher level ship design or survivability objectives;

5. It is not possible, in general, to screen other materials on the basis of the small-scale tests;

6. If improved materials become available in the future, the entire process with its limitations must be repeated; and

7. Since material behavior and its shipboard impact cannot be related; cost/benefit and other trade-offs (e.g., active systems) cannot be integrated into the process.

One goal, therefore, is to seek methods which may eliminate these drawbacks and offer qualitative advantages for similar development costs. The essential technical goal would be a system which enabled one to accomplish the following:

1. Establish required small-scale test performance based on full-scale performance objectives; and

2. Specify materials based on required small-scale test results.

This requires that it be technically possible to relate full-scale performance to small-scale material flammability properties via correlations or mathematical models. This report will demonstrate that for some applications such a direct cross-connection is possible, but has not been generated for materials and applications of general interest to the Navy and cannot be done in general. However, modified approaches which preserve the benefits desired and are in general technically feasible are proposed in this report. More importantly, improvements can be expected immediately or near term.

The remainder of the report discusses in more detail the philosophical and technical problems and proposed solutions to meet the objective of a more rational performance base to material selection and specification.

2.0 FIRE PERFORMANCE OBJECTIVES

The overall objective of setting material fire requirements is to minimize the occurrence of fire and limit its consequences. These broad objectives can be further reduced to a qualitative statement of requirements:

1. Ensure materials are not readily ignited;

2. Ensure that small fires do not grow quickly;

3. Maximize the time available before human tenability and/or equipment damage limits are reached;

4. Minimize the occurrence of flashover or complete compartment involvement; and

5. Ensure the fire containment, structural and mechanical functions of boundaries under fire conditions.

These requirements are similar to the objectives stated in the development of fire performance criteria for composite materials used onboard ships. These objectives are of course relatable to flammability and other fire characteristics of materials and assemblies. For example, Objective 1 can be related to ignition delay times of materials exposed to a fixed radiative heat flux. Alternatively, Objective 1 can be related to the performance of materials in bunsen burner-type small-scale tests. The key requirement is that one be able to measure or calculate the full-scale performance of materials based on small-scale results such that these real-scale performance measures are met. The purpose of the section is to provide a discussion and recommendations relative to setting objectives.

2.1 Top Level Approaches

Agreement on the performance objectives desired is a prerequisite for the development of a sound plan for future passive fire protection program endeavors. Ideally, one would like to state these objectives in terms of a measurable impact on Navy operations. Examp'es of performance objectives include the following:

- Ensure that no peacetime fire on board a U.S. Navy ship results in damage exceeding $20,000.00; or

- Ensure that no peacetime fire on board a surface combatant results in any degradation in the ship's primary and secondary warfare systems; or

- Ensure that combat-induced fires do not spread beyond the initial compartment of origin (hence limiting combat damage to local effects).

The basic problem with establishing objectives like these is the difficulty in measuring success. Bearing in mind the almost infinite range of fire initiation scenarios, fuel loading configurations, damage scenarios, active firefighting measures, etc., and the probabalistic nature of these parameters, measurement of success can degenerate into a numbers game. This is particularly true when one starts with a flammability property and intends to determine the post-fire state of a particular ship's specific weapons systems. A more detailed critique of these types of fire risk assessment methods can be found in DiNenno and Beyler (1990).

Another top level approach is to force any passive fire protection improvement to pass a cost/benefit test. For example, no passive fire protection improvement should be undertaken unless its benefit exceeds its cost. The problems with this approach include those previously stated plus the additional difficulties associated with defining benefit, particularly in the context of military systems.

2.2 Proposed Performance Requirements

A more reasonable approach may be to further quantify the objectives related to real-scale fire performance. This approach has the advantages of being directly measurable and could be, if desired, related to more top level performance objectives.

One framework for evaluating the performance of materials is the concept of an allowable change in hazard caused by a material. Figure 1 illustrates this concept. An "exposure" fire by itself will result in a certain temperature, smoke obscuration, and gas concentration in a compartment. The goal of regulating materials is to limit the degree to which the material exposed contributes to the baseline fire. Material A in Fig. 1 would be acceptable, i.e., it would meet performance objectives if the 'material contribution' is below some threshold. Performance as indicated in Material B would be unacceptable.

The following performance requirements are suggested as examples. These objectives are derived from performance objectives previously developed by the Navy for shipboard use of composite materials. They will clearly require refinement as consensus is developed.

A. *Ignition*

1. No material should be ignited when exposed to a flame source equivalent to a bunsen burner (or match) for a period of 60 seconds.

2. No material should ignite when exposed to a small exposure fire (50 kW, a small trash basket) for a period of 300 seconds. (This translates to a peak exposure of approximately 50 kW/m^2.)

3. No material should ignite when exposed to a heat flux level of 75 kW/m^2 for a period of 60 seconds. (This is approximately the peak heat flux from a 200 kW exposure fire.)

B. *Fire Growth*

1. No wire/cable or bulkhead insulation, sheathing, flooring, or other interior finish shall contribute more than 50 kW of energy when exposed to a 200 kW source fire.

2. No interior finish material shall result in flame spread beyond the initially exposed area when exposed to a 200 kW source fire for a period of 600 seconds.

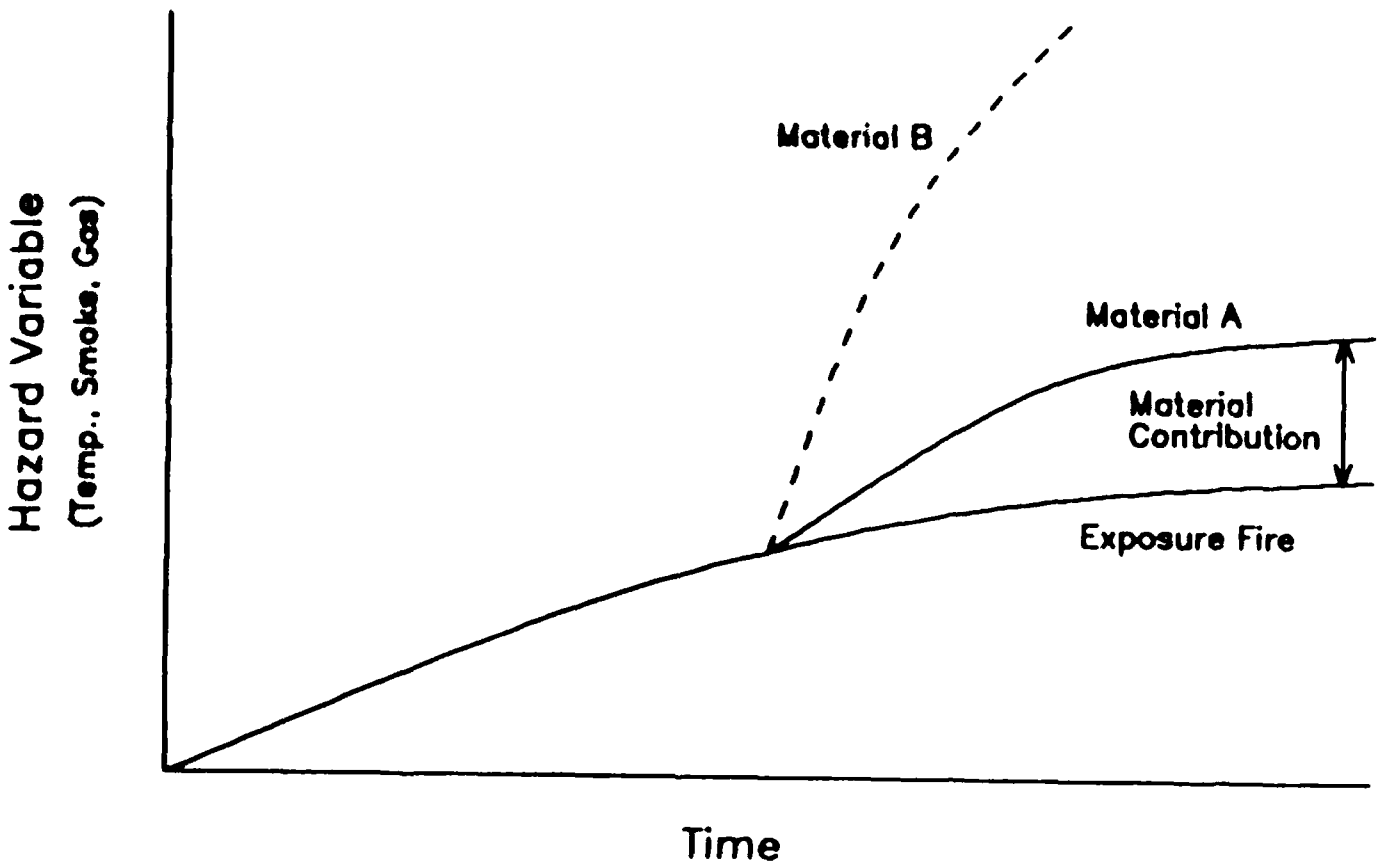

Fig. 1 - Allowable incremental hazard

3a. No furnishing item shall contribute more than 50 kW when exposed to a 200 kW source fire; or alternatively

3b. The heat release rate of a furnishing item when exposed to a 200 kW source fire shall not exceed that which will cause flashover in a compartment (approximately 800 kW for an insulated 10 ft cube with door open).

C. *Tenability*

1. Visible smoke production will be limited such that the material when exposed to a 200 kW exposure fire does not release sufficient smoke to reduce visibility below 30 ft in a typical compartment for a period of 300 seconds.

2. Smoke toxicity will not be greater than 2x, the normally accepted smoke toxicity limit.

3. Smoke corrosivity shall be limited such that electronic equipment damage shall not occur at levels greater than expected for a 200 kW hydrocarbon fire in a typical compartment when burning for a period of 600 seconds.

D. *Fire Resistance*

1. Fire zone boundaries shall have sufficient thermal insulation, structural, and mechanical properties to provide a minimum of 30 minutes of fire resistance such that ignition of combustibles on the unexposed side does not occur. The fire threat shall be indicative of a ventilation pressurized post-flashover compartment fire

2. Mechanical or structural elements requiring fire endurance shall maintain their integrity under the exposure conditions of D.1.

These requirements assume that one can define fire performance in the context of the threat or exposure to individual compartments. The assumptions and basis for this approach is as follows:

a. It is not possible to eliminate ignition sources and control <u>all</u> combustible materials on board ship. Hence, these "uncontrolled" items form "threats" to controlled materials. This further implies that uncontrolled items do not form a significant fire threat in an of themselves. Examples of those types of exposures include wastebaskets, incidental combustibles (seabags, paper, etc.), shipyard/maintenance fires, etc.

b. If one can design a ship or specify materials to survive these small exposure fires, one can materially control the incidence and severity of fires.

c. The performance of individual components (e.g., mattresses, cables, bulkhead sheathing, and deck covering will be indicative of real world (system) performance for most of the time history of the fire development process. This assumption implies the following:

1. it is not necessary (in general) to understand all of the interactions between all combustibles in a compartment; and

2. one must set performance criteria such that fires do not grow to a size where such system interactions are important.

Figure 2 illustrates the concept of treating compartments (e.g. wall linings or rack of bunks/mattresses) independent of the compartment. At some point in a fire development curve, the temperature in the compartment is raised to a point where significant heating of uninvolved combustibles occurs. This is typically in the range of 200-300°C. This also implies that the fire has grown to a threatening level. Before this point in time, the material and/or the exposure fire behave effectively as if they were burning in the open (assuming geometry effects such as corners are accounted for).

Hence, the impact of compartment effects can be ignored. Beyond this point of time, the compartment heating effects become significant. Tenability, visibility, and non-thermal equipment damage are already problems. With another 200-300°C increase in temperature, the compartment will flashover. Hence, for issues associated with fire growth, tenability, toxicity, etc., attention can be focussed on this initial growth phase and more importantly, the behavior of these materials studied independent of each other and compartment effects. A possible exception to this approach is in the area of certain interior finish flame spread problems where modest surface heating of unburned wall linings ahead of the flame front may be significant.

d. The performance of individual components or materials can be related to damage, temperature, heat flux, smoke, gas concentrations, etc., in a compartment, which are the primary fire effects variables of interest.

This approach has been accepted as the basis for the regulation of composite materials on submarines. It is also the basis for state-of-the-art hazard and risk assessment methodologies [DiNenno and Beyler (1990)].

It is important to recognize that the performance limits, including time frames, can be varied by ship class, compartment type, relative amount of material, fuel load, or any other variable that impacts the fire hazard or risk associated with a particular material usage. Such variables may also include provision of detection systems, fixed or automatic systems and may account for some assumed level of manual firefighting.

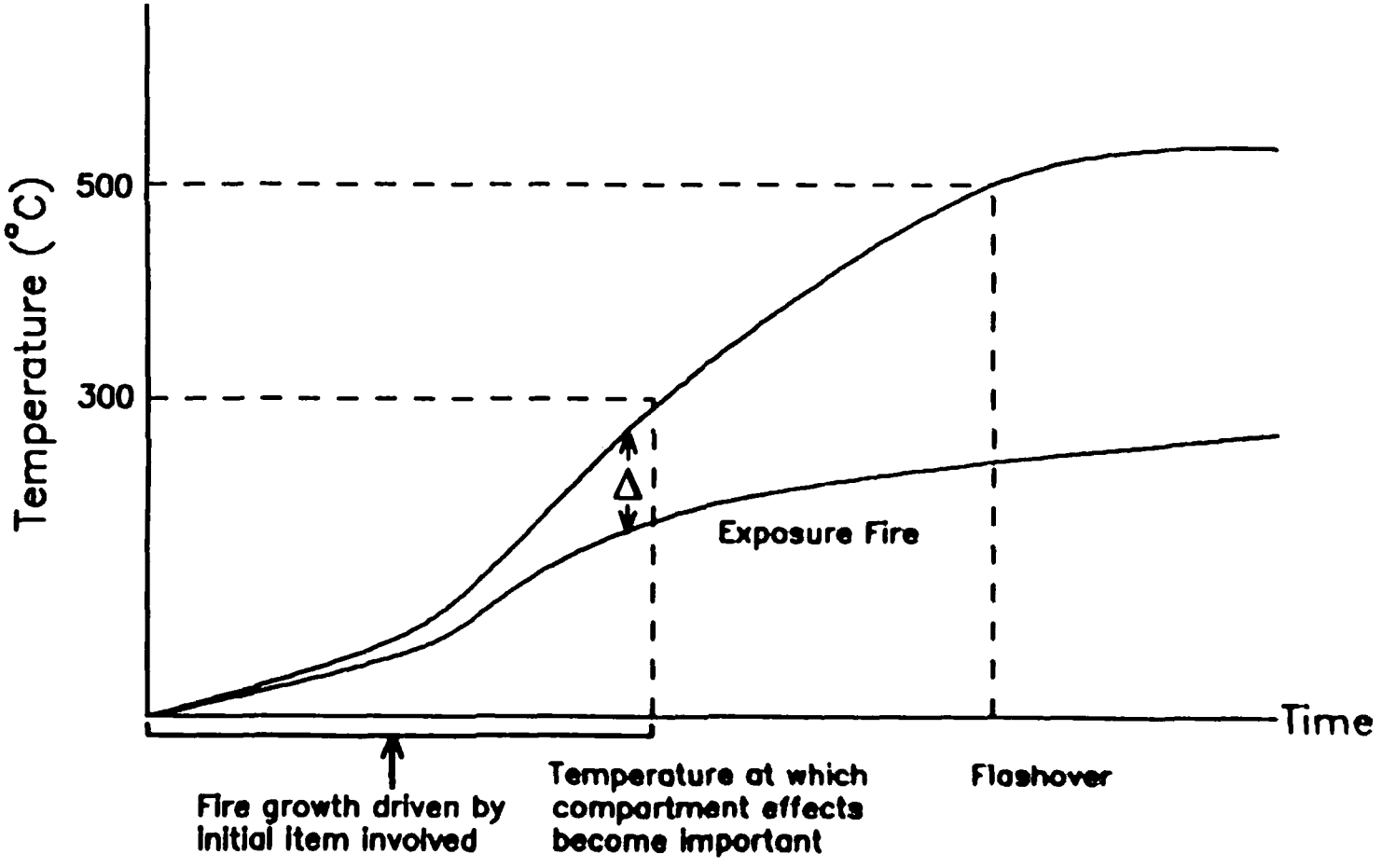

Fig. 2 - Fire development curve

Consensus on these performance objectives and their quantitative base must be reached. The primary variables in these objectives are size of exposure fire and time frame of exposure.

2.3 Exposure Fires

The recommended approach assumes that most materials regulated under the passive fire protection program are subject to external threats. These external threats or exposure fires are not subject to a priori control. The range of possible exposure fires goes from matches through unexpended missile fuel fires. For purposes of analyzing fire growth, the range of interest in exposure fires is from 0 to approximately 500 kW. At 500 kW, the exposure fire itself is a threat to the compartment. A 200-250 kW exposure represents a large waste container or packed polyethylene trash bag with combustibles inside. It is equivalent to a pool fire of one ft^2. It is deemed a reasonable "worst case" exposure fire for purposes of evaluating fire growth contribution.

There is of course an extremely wide variation in the size of possible exposure fires. Table 1 summarizes some of the data for "small," incidental exposures.

At the other end of the spectrum are the exposures posed by post-flashover fires (and their analog, unexpended missile fuel fires). These fires will result in temperatures approaching 1000°C or radiant heat fires on the order of 200 kW/m^2. The primary interest in these exposures is the behavior of fire zone boundary materials and structural elements which are required to maintain their integrity under fire exposure.

One indicator that it may be possible to design materials to withstand the exposure of an unexpended missile fuel fire lies in the result of the HULVUL tests and related trials [Leonard et al. (1991); Leonard and Farmer et al. (1993)]. Table 2 summarizes a small subset of data on heat fluxes at the floor, ceiling, and in the vicinity of the unexpended burning solid missile fuel. While the heat fluxes are quite high, the durations are low, typically on the order of one minute. This coupled with the observation that oxygen levels in the compartment during these peak heat fluxes are quite low indicate that materials may be available that either will not ignite or the resultant fires will not grow quickly, even under these extreme but short lived exposure conditions.

The time scales associated with the performance objectives are based on several parameters. These include the following:

1. expected duration of exposure fire;
2. critical time(s) for intervention; and
3. minimum times for "graceful degradation."

The difficulty in pegging the performance criteria to the exposure fire duration lies in the probabelistic nature and uncertainty in the character of these threats.

Table 1. Typical Exposure Fires

Item	Peak Heat Release (kW)	Duration (>50% peak) (sec)
Range of PE, 6 l trash container	50	200
Trash bag, 2.5 lb	125	120
Trash bag, 7.5 lb	350	180
Trash (20 kg/m^3)	300-350	
Trash (100 kg/m^3)	50-100	
Trash Basket (1 lb)	4-15	
Mail bags, 4.5 ft stack	400	
Curtains (cotton)	130-600	
Curtains (acrylic)	231-1177	
JP-5 pool (1 ft^2)	230	
JP-5 pool (100 ft^2)	2300	

Table 2. Selected Summary Data for Missile Fuel Exposures

Test 11	210 lb fuel	5-10 ft:	
		165 kW/m^2 peak	
		time from start to end of peak	30 sec
		Floor:	
		40 kW/m^2 peak	
		time frame	90 sec
		Ceiling:	
		32 kW/m^2 peak	
		time	120 sec
Test 12	150 lb fuel	5-10 ft:	
		150 kW/m^2 peak	
		time	30 sec
		Floor:	
		42 kW/m^2 peak	
		time	45 sec
		Ceiling:	
		45 kW/m^2 peak	
		time	60 sec
Test 13	200 lb fuel	5-10 ft:	
		250 kW/m^2	
		time	45 sec
		Floor:	
		50 kW/m^2 peak	
		time	45 sec
		Ceiling:	
		25 kW/m^2	
		time	50 sec

Critical times for manual intervention are a subject of great debate. In the submarine community, a response time (pessimized) of 300 seconds is assumed reasonable. This issue has never been directly addressed for surface ships and is known to be a complex function of fire location, time to detection, type of fire, ship readiness condition, etc.

The proposed criteria would require performance for longer time periods under smaller exposure fires (e.g., 300 seconds for 50 kW exposure fires vs. 60 seconds for 200 kW exposure fires).

The rationale for this approach lies in the time dependence of the exposure fire development, i.e., 60 seconds for a 200 kW exposure fire is in addition to the 300 seconds for a 50 kW exposure fire. It should be remembered that these values at this point are arbitrary and the important issue is a recognition that this approach to setting performance objectives is acceptable.

In order to relate an exposure fire of known size (heat release rate) to material behavior, the relationship between exposure fire and heat flux must be known. There have been several attempts at accomplishing this, the most useful data coming from propane burners. Figure 3 gives peak heat flux vs. exposure fire size for exposure fires ranging from 50 to 500 kW. The fire source is located against a wall and the heat flux measured at the wall. The notable finding of this work is that the peak heat flux does not vary greatly with fire size. Between 100 kW and 300 kW in fire size, the flux ranges from 60 kW/m^2 to 90 kW/m^2. These are relatively high flux levels. Figure 4 demonstrates that this heat flux is attained over 50% of the exposed area.

These flux levels are probably conservative in that the fuel is propane gas with a relatively high flame emissivity. However, normal combustible fires of similar heat release rates are expected to yield lower flame emissivity but not substantially lower heat fluxes. It is reasonable, however, to use gas burners as "design basis" exposure fires for purposes of full-scale testing. This approach has been recently supported by Mowrer and Williamson (1991).

2.4 Conclusions

Based on the foregoing discussion, the following conclusions may be reached regarding fire performance objectives:

1. Fire performance objectives can be stated in quantitative deterministic terms.

2. Fire performance objectives for materials should be related to the incremental hazard posed by a material.

3. The performance requirements of materials should be cast in the context of the threat to these materials, in this case size and duration of an exposure fire.

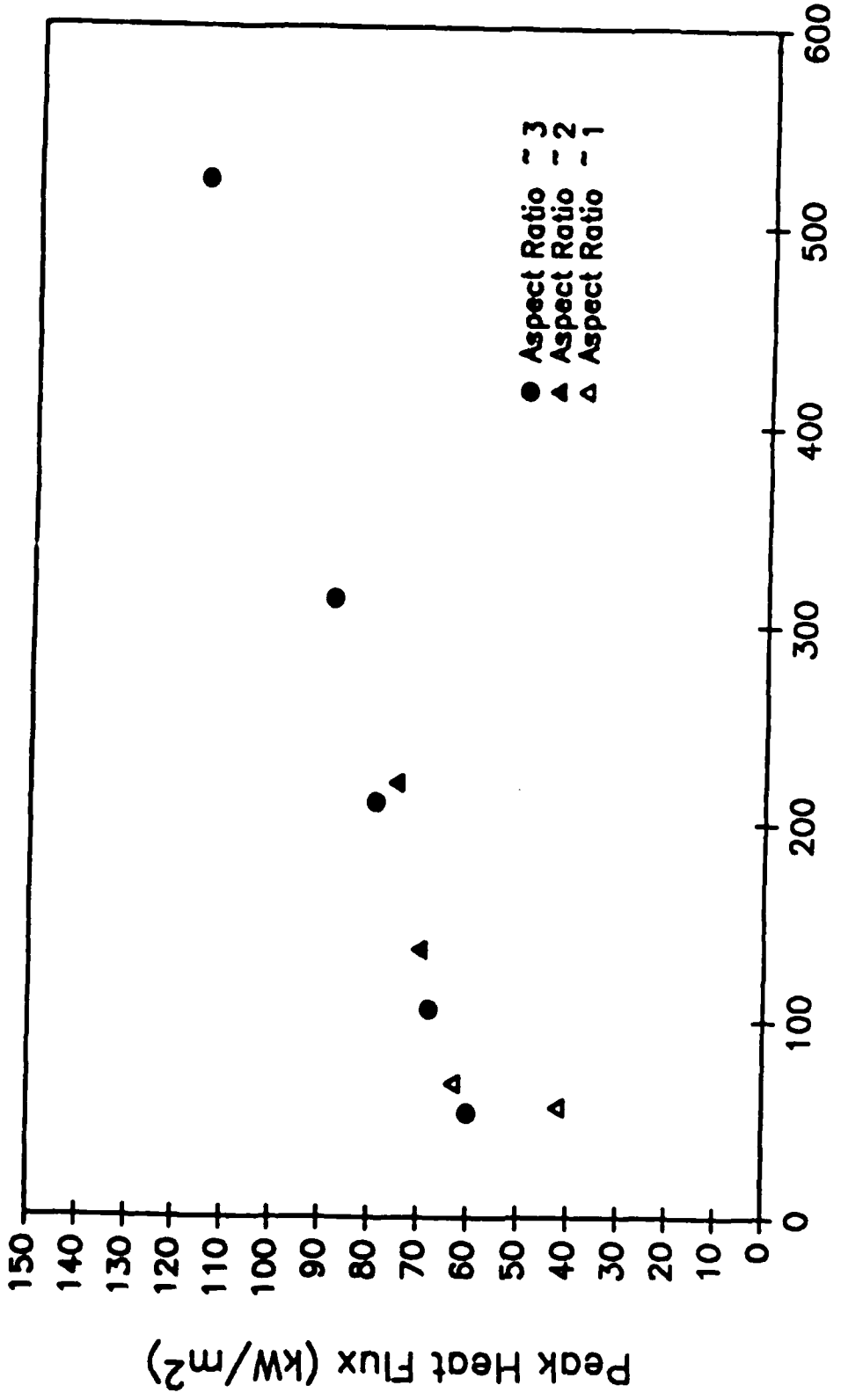

Fig. 3 - Peak heat flux for typical exposure fires

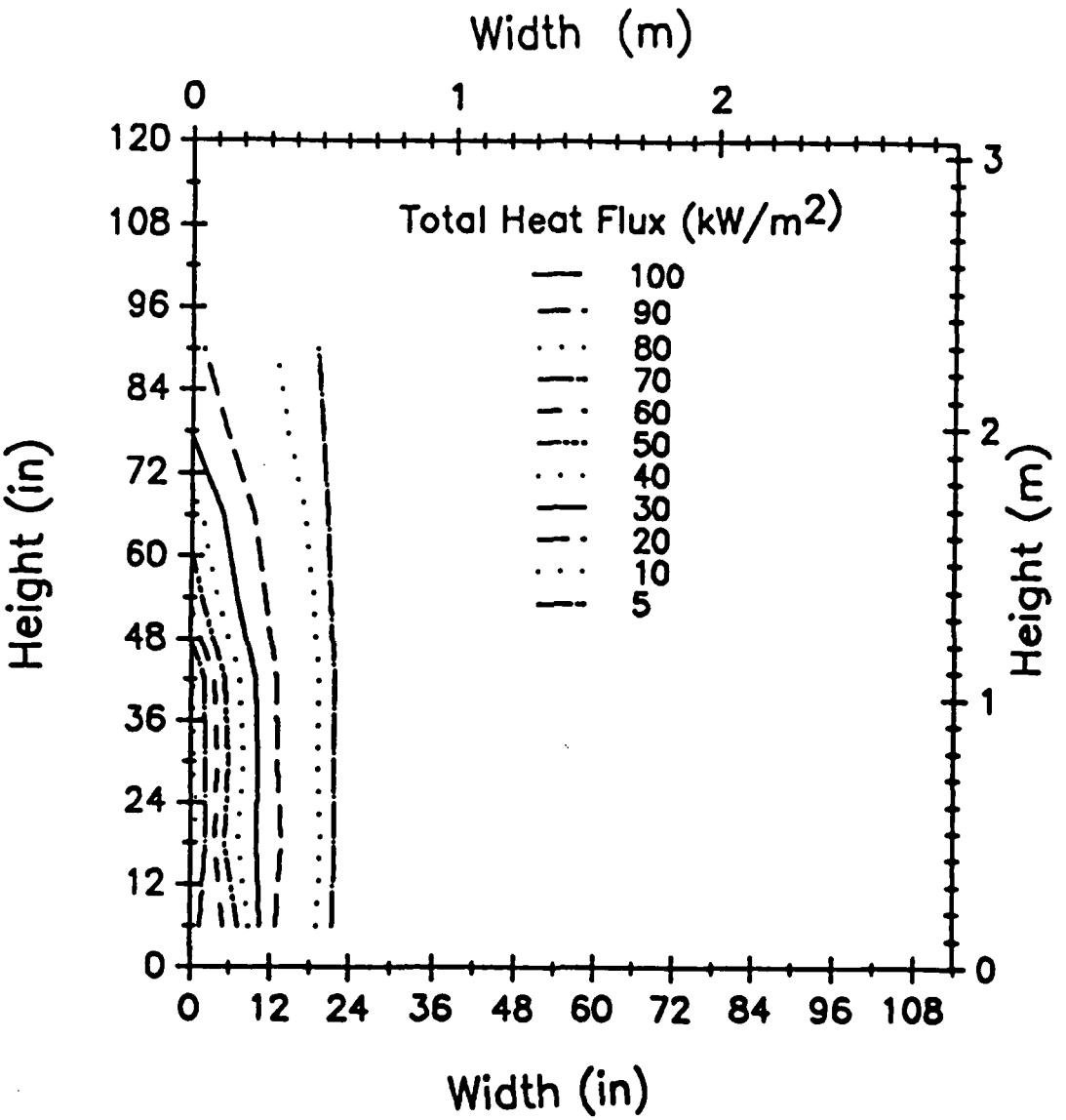

Fig. 4 - Heat flux map for a 22-inch burner with a 66-inch flame height (313 kW fire)

4. If this approach is acceptable, further work in this study should be directed toward quantifying and justifying the objectives.

5. The proposed "acceptable incremental hazard" criteria can be varied by compartment, material application, and/or the existence of automatic suppression systems.

3.0 FLAMMABILITY TEST METHODS

3.1 Review of Test Methods

Current Navy material specifications utilize a wide range of flammability test methods. They range from very simple bunsen burner tests to the ASTM E 84 Steiner tunnel. With the exception of requirements for composite materials, all of these test methods possess the characteristics that the results obtained cannot in general be related to full-scale performance. Appendix A summarizes the current habitability, wire and cable, and packaging specifications relative to material type and application, test method, and acceptance criteria.

Appendix B gives a brief description of each test method. While it is well known that most of these test methods may give misleading or incorrect results relative to full-scale performance (there is a caveat at the beginning of each ASTM standard listed to the effect), it should not be assumed that these materials are unsafe or not suitable for shipboard use. This is due to the fact that the specification describes a generic type of material (e.g., melamine) in a specific application (e.g., bulkhead sheathing) such that the test method results help to describe the material the Navy wants based on some full-scale testing or other knowledge prior to the specification being written.

An example of the utility and relevance of existing shipboard flammability requirements can be seen in the requirements for berthing spaces. The flammability requirements for habitability spaces are derived from analysis and full-scale testing by Lee and Parker (1976, 1979). As early as 1976, it was proposed that rate of heat release be included as a regulated flammability property. At that time, however, only experimental heat release rate devices were available. The results of these tests and analysis indicate that the combination of small-scale flame spread (ASTM E 162) and smoke properties (ASTM E 662) given in MIL-STD-1623[1] for berthing spaces, particularly mattress and mattress covers, yielded adequate performance under small flaming ignition sources (<10 kW) applied directly to bedding/mattresses.

The results of these early studies developed interesting findings relative to the behavior of materials in berthing spaces. These included the following:

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[1] Full titles of ASTM test standards and Military standards and specifications are given in the Reference section.

1. The enclosure of three of four sides (with a curtain) of a bunk had substantial impact on this fire growth of the bunk.

2. If an ignition delay time of >60 seconds could be obtained from the NBS ease of ignition apparatus, the growth rate was expected to be substantially lower. The ease of ignition test, consisting of two parallel samples with a two-inch gap exposed to a burner flame, yields a heat flux of approximately 32 kW/m^2 over a small sample area.

3. The analyses were the first to attempt to "model" the fire growth and resultant hazard using small-scale methods and simple mathematical models. The success of the effort relative to modeling was mixed, primarily due to the relatively early (and crude) mathematical models and the limited test methods.

4. The importance of rate of heat release of the mattresses (a major fuel component) was noted.

5. Rates of heat release of interior finish materials were measured and limits proposed.

6. Requirements for interior finish material were based on time to ignition, flame spread (ASTM E 162), critical heat flux for flame spread (early LIFT), heat release rate, potential heat and smoke (ASTM E 662). Criteria varied depending upon the limitation of the material (overhead, bulkhead, or deck). The rate of heat release values measured for melamine and vinyl laminate exhibited relatively high rates of heat release at 20 to 60 kW/m^2 exposure, even though flame spread values were low (<25, ASTM E 162).

7. "Full-scale tests" were conducted in an approximate 10 ft x 10 ft x 8 ft (H) compartment.

These tests and analyses demonstrated that, at least for small flaming ignition sources, a combination of small-scale test methods and a generic description of the component (e.g. neoprene mattresses) were developed; the effective control of flammability properties was achieved. These pioneering studies also form some of the earliest efforts to "calculate" full-scale performance based on small-scale results. They further demonstrated the need for improved test methods and, in particular, the importance of rate of heat release as a flammability property.

Rather than describe individual weaknesses with the test methods, this report focuses on what the future direction the passive fire protection program should take. The advent of newer test methods enables more direct connection between small-scale results and real world performance. Since the objective is to develop and/or choose materials on the basis of performance objectives, such test methods are required.

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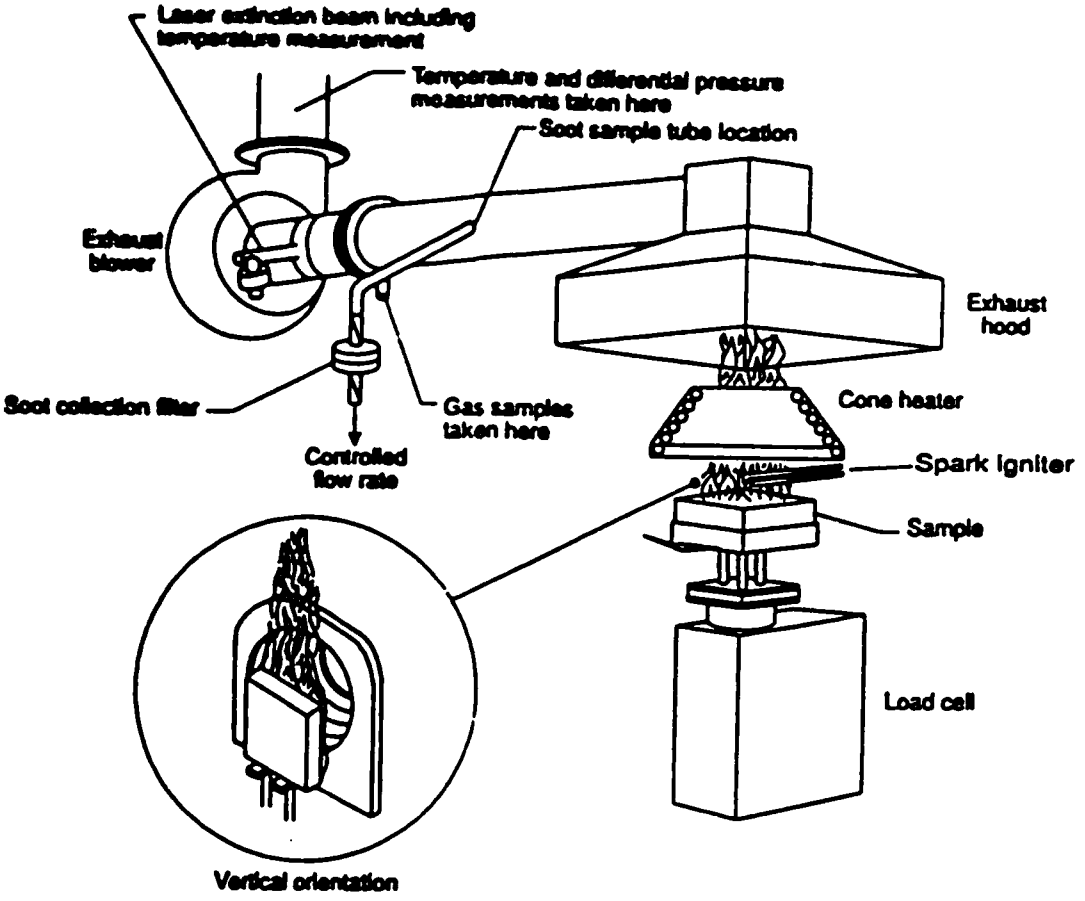


Fig. 5 - ASTM E 1354 Cone calorimeter

In the cone calorimeter, specimens of a material or product to be tested are cut into a 100 x 100 mm size. The thickness depends on the type of product tested and can range from 6 to 50 mm. The specimen edges are protected from burning, and the specimen can be oriented either horizontally or vertically. The specimen is heated by an electric heater in the shape of a truncated cone, hence, the name cone calorimeter.

The irradiance to the specimen can be set to any desired value from zero to 110 kW/m^2. This irradiance can be related to the exposure to the material. If required, external ignition of the specimen is provided by an electric spark. Since a uniform, contr " d irradiance is provided, the ignition times themselves, as measured, constitute a ' ' e test for ignitability. The specimen is mounted on a load cell, and its mass, along with all other instrument data, are recorded to provide mass loss rate data. The smoke measuring system is comprised of a He-Ne laser beam projected across the exhaust duct. The monochromatic light is monitored by a solid-state detector. A second detector serves as a reference to guard against effects of drift and of laser power fluctuations. The optical system is designed to be self-purging and does not use optical windows. To specify the test conditions fully requires specifying the irradiance, the specimen orientation, the use of spark ignition, the test irradiance, and any special specimen preparation techniques.

The data to be derived from the bench-scale tests in the cone calorimeter constitute a very large set and can be analyzed in a multitude of ways. The data reported include the following:

(a) peak rate of heat release (kW/m^2);

(b) rates of heat release averaged over various time periods, starting with the time of ignition (kW/m^2);

(c) effective heat of combustion (MJ/kg). This will be less than the oxygen-bomb value of the heat of combustion since the combustion is incomplete;

(d) percent specimen mass lost (%);

(e) time to ignition (s);

(f) average smoke obscuration (m^2/kg). Smoke production from a material has the rational units of m^2, representing the extinction cross-section of the smoke. This is normalized by the amount of specimen mass lost (kg); and

(g) average yields of each of the measured gas species (kg/kg).

Each of these parameters can in principle be related to full-scale burning behavior of a material.

3.2.2 ASTM E 1321, LIFT Method

The LIFT Method combines two separate test procedures: one to determine ignition and the other to determine lateral flame spread.

The sample holder fixes the specimen in a lengthwise vertical orientation. A radiant panel is positioned parallel to the sample at a 75° angle from the perpendicular. The layout is represented in Fig. 6. The ignition test requires samples, 150 x 150 mm, which are exposed to a nearly uniform heat flux. A series of tests at different flux levels are used to develop an ignition time versus the radiant flux profile. From this profile, the minimum flux for ignition is determined.

The flame spread tests use 150 x 800 mm samples. These samples are exposed to a graduated heat flux which is 10 kW/m^2 higher than the minimum flux calculated above at the hot end. The specimens are preheated for a time which is based upon ignition test results. A horizontal pilot is ignited after the preheat time is over. The flame spread rate on the sample is then recorded.

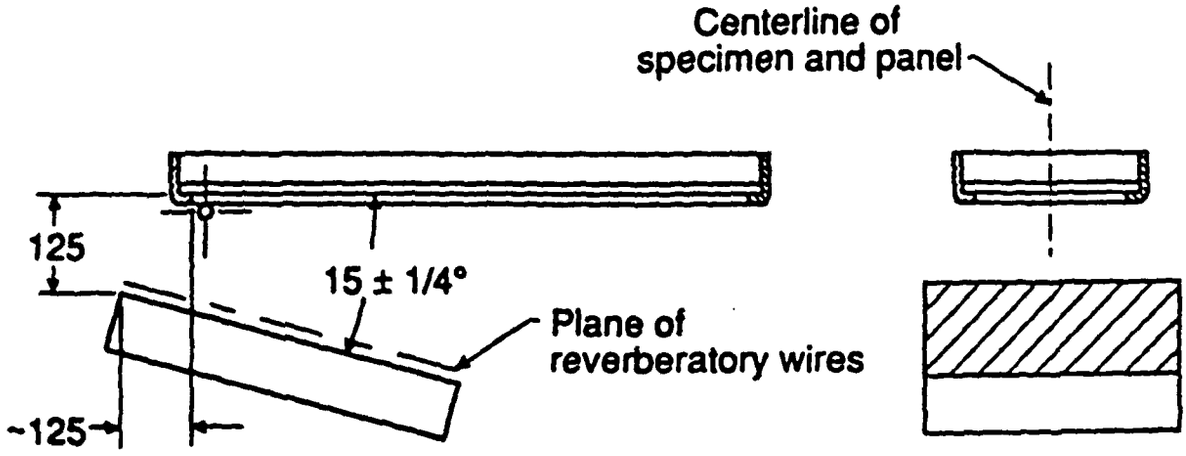
Data reported include minimum flux for ignition, surface temperature necessary for ignition, thermal inertia value, the flame heating parameter, and flame front velocities.

It must be recognized that at some point in the development of a fire, increased temperature and reduced oxygen in the compartment affect the burning behavior of the material of interest considerably. It is explicitly stated that the time span of interest relative to ignition, fire growth, and tenability requirements occurs before any significant compartment/fire/material interaction. This is a logical limitation in the sense that controlling fire growth and development is best done prior to compartment wide damage and most definitely prior to flashover. The basic idea here is to establish limits on those compartment hazard variables and work backward to a set of small-scale test results.

The question is, of course, is such an approach possible. The response is a qualified yes, in the sense that such scaling has been demonstrated for some applications.

Figure 7 is an illustration of the process of relating small-scale test results to full-scale. There are effectively two steps. The first requires predicting the burning characteristics of a material in a specific application. Characteristics of interest include

- heat release rate, Q, (kW) as a function of time;
- sample mass loss rate;
- smoke yield;



NOTE—All dimensions are in millimeters.

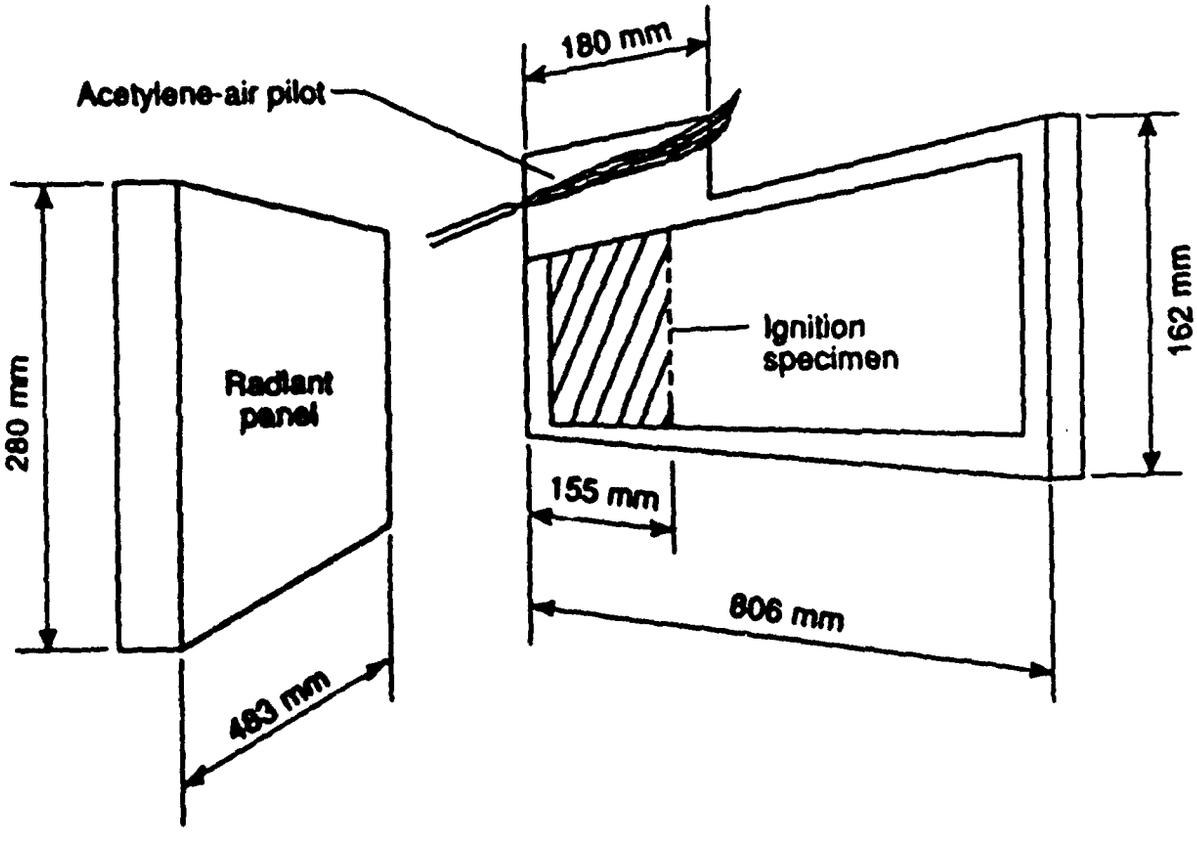


Fig. 6 - ASTM E 1321 test apparatus

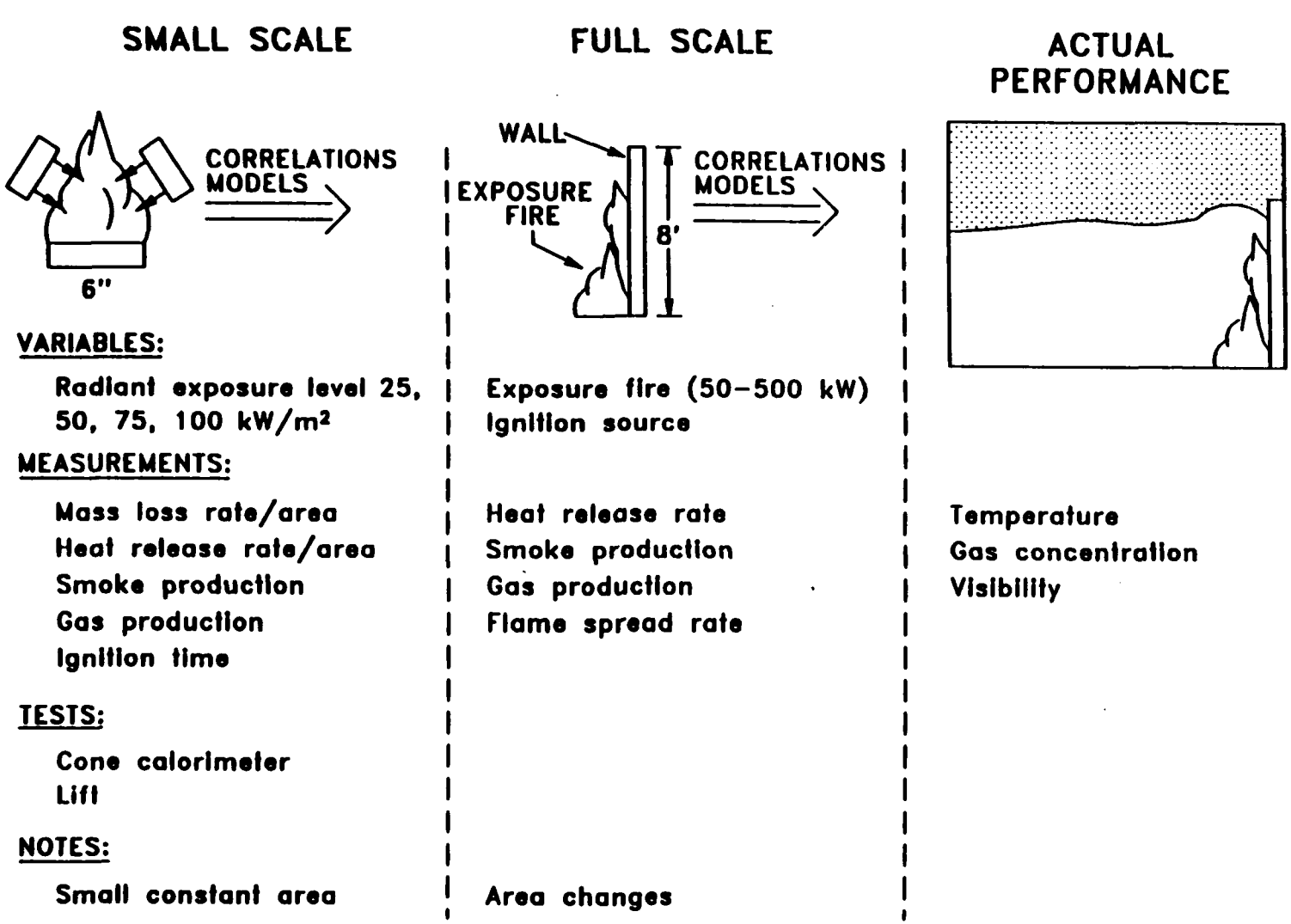


Fig. 7 - Structure of fire hazard analysis system

- smoke optical properties; and
- (toxic) gas production rates.

In general, the prediction of these full-scale burning characteristics requires a set of correlations or a mathematical model which relates small-scale properties to these full-scale results.

While there has been some success in "scaling up," most notably in the area of upholstered furniture and more recently in regard to flame spread over interior finish materials, it should not be assumed that "canned" schemes exist for all materials in all applications. It should be noted, however, that there is no reason at present to believe that flammability characteristics measured with more modern test methods do not yield reliable (in full-scale) indicators of performance. The difference between the two being how good the scaling relationships or models perform, not one of test method validity.

3.2.3 Quantitative Basis for Relating Material Flammability Properties to Fire Performance Measures

Prior to addressing the extent to which these small-scale test methods can be related to full-scale performance, it is useful to describe some of the relatively simple relationships between the small-scale flammability data and full-scale hazard measures. While certainly not exhaustive, this discussion describes the concept of scaling or relating small-scale test results with real-scale performance. It is not intended to be in any sense a final description of "how to scale" these results.

The flammability of a material has little meaning in and of itself. The proposed use of a material, its environment, and possible exposure fires will determine to what extent a material contributes to the hazard posed by a given fire scenario. In this section, the basic hazard concept developed in Section 2.0 is described in terms of the relevant quantitative relationships. Analytical methods for calculating critical hazard parameters are presented. A quantifiable framework is developed to characterize burning materials, in terms of quasi-steady burning and lateral flame spread. The input parameters used in this model (e.g., framework) are derived from two small-scale test methods; the cone calorimeter and the LIFT/IMO flame spread apparatus. The derivation of these input parameters are provided in the context of the particular small-scale test.

A. HAZARD VARIABLES

Several variables, including temperature, smoke visibility levels, and toxic gas levels are typically used to measure the relative fire hazard associated with survivability, damagability and mission criticality. The relationship between these hazard variables and material flammability characteristics can be expressed quantitatively. These are meant to be example calculations to demonstrate the cross walls between small-scale properties and fire hazard.

1. Temperature

Temperature is directly proportional to heat release rate, a critical material flammability parameter. In turn, the rate of heat release is a strong function of the thermal exposure to the material. This thermal exposure is the direct result of the fire size, and if the fire is located in an enclosure, it is also dependent on the temperature conditions in the enclosure.

Relatively simple correlations are available which relate the heat release rate from a fire to the enclosure temperature. For example, a simplified expression for estimating enclosure temperature for enclosures with noncombustible linings is

$$T = T_o \left[1 + \frac{0.0236\ \dot{q}^{2/3}}{(h_k A A_v \sqrt{h_v})^{1/3}} \right] \qquad (1)$$

where

T	=	upper gas temperature
T_o	=	ambient gas temperature
q	=	heat release rate
h_k	=	enclosure conductance
A	=	surface area of enclosure
A_v	=	vent area
h_v	=	vent height

This expression can be used for the simple case of natural ventilation to estimate the temperature rise in an enclosure due to the burning of a material, providing the heat release rate parameters are known. Similar, but more complicated expressions are available for enclosures with combustible linings or forced ventilation.

Note that heat release rate is the only material parameter in the correlation. The remaining parameters are dependent on the geometry and construction of the space where the material is used. Furthermore, the material's heat release rate is a function of the thermal exposure and the surface area of the material exposed, both of which are scenario and material application dependent. These relationships demonstrate the importance of evaluating a material in terms of its intended use.

2. Smoke Visibility

The effect of smoke particulate production and transport on human visibility is considered a critical fire hazard parameter with regard to survivability and mission criticality. Quantitatively, for a closed space, visibility can be related to material characteristics and its application based on

$$V = C\left(\frac{\sigma_m \Delta m}{V_c}\right)^{-0.67} \quad (2)$$

where

V	=	visibility distance
σ_m	=	specific extinction area
Δm	=	mass of material burned
V_c	=	enclosure volume
C	=	a constant

The mass of material burned is a function of the thermal exposure to the material, the area of material exposed, and the time the material has been burned. The mass loss rate per unit area is strongly dependent on the thermal insult to the material. The time dependence of visibility is driven by the time dependent nature of the burning rate. In general this dependence is expressed as

$$\Delta m = \int_{t_o}^{t} \dot{m}'' A_f \, dt \quad (3)$$

where

Δm	=	mass of material burned,
$\dot{m}''$	=	mass loss rate per unit area,
A_f	=	area of fire (surface area of material involved), and
t	=	time.

In general, $\dot{m}''$ will be a function of time as well as the surface area of fuel involved. For steady fires, this can be simplified to the following:

$$\Delta m = \dot{m}'' A_f t \quad (4)$$

3. Toxic Gas Generation

The concentration of toxic products can be related to hazard variables such as incapacitation or death. The production of toxic gases is a function of the material used and the environment and application under which it is expected to burn or be exposed to fire. Limits on allowable concentrations of toxic gases or combinations of gases can be set if all important toxicants can be identified a priori. The yields of these compounds (kg of gas n per kg of fuel burned) can then be related to the burning rate of the material.

For conditions where the yield of gas n is constant with time, the mass fraction of gas n in the upper layer of a compartment fire can be estimated as follows:

$$M_n = \frac{\int \dot{m}'' A_f \psi_n \, dt}{m_L} \quad (5)$$

where

M_n = mass fraction of gas n
$\dot{m}''$ = material mass loss rate
ψ_n = yield of gas n
A_F = surface area of material involved
m_L = mass of layer gases

Recall that both $\dot{m}''$ and A_f can be functions of time depending on the thermal exposure and flame spread properties of the material.

The concentrations of toxicants can be related to incapacitation or death through the N-gas models used in combustion toxicity. Interactions between carbon monoxide, hydrogen cyanide and oxygen depletion are typically considered. Dose levels resulting in death are derived and related to actual gas concentrations in a particular application under a specific ignition and fire growth scenario.

B. FRAMEWORK FOR EVALUATING MATERIAL PROPERTIES

As demonstrated in the previous discussion, parameters used to evaluate the hazard under specific conditions can generally be related to selected material flammability parameters. Hazard variables such as temperature, smoke visibility and toxic gas production can be related directly to material characteristics such as heat release rate, flame spread, mass burning rate, smoke properties and gas species yields (all measurable by small-scale test methods). Further, as discussed in Section 1.0, evaluation of material flammability characteristics without consideration for its intended use and potential exposure scenarios is simply incorrect. The importance of a particular hazard variable or its time dependence (e.g., temperature) will be effected by end use parameters which are entirely independent of the material. For example, the relative importance of temperature with respect to visibility is expected to change depending on where the material is used (e.g., electronic space vs. airframe application).

1. The Use of a Pool Fire Analog

The issue of combustibility and related fire characteristics of composites can be evaluated in the context of several different frameworks. The most widely used is the analog of a burning material to a liquid pool fire. This very simple analog preserves the most important aspects of material fire behavior given the current state-of-the-art in testing. Both steady state and unsteady state scenarios can be evaluated. This framework is consistent with current hazard assessment and modeling procedures and represents the best available use of small-scale test methods.

2. Quasi-Steady Fire Conditions

The simplest application of the pool fire analog to burning composite materials can be described in terms of a horizontal slab under quasi-steady burning. The two critical parameters are burning rate and flame spread. Burning rate can be expressed as mass loss rate, and can be estimated by

$$\dot{m}'' = \frac{\dot{q}_f - \dot{q}}{\Delta H_{vap}} \tag{6}$$

where

m''	=	mass loss rate
q_f	=	heat flux from flame
q	=	energy loss terms
ΔH_{vap}	=	effective heat of vaporization

The heat flux from the flame is comprised of both convective and radiative terms with the radiative terms dominating. The loss terms include conduction, convection and reradiation losses from the fuel surface. External heat gain terms, such as radiation from other burning objects or from heating gas layers in compartments can be included simply by adding the energy term from external sources (q"e) in the numerator of equation 6.

In turn, several important hazard parameters can be determined by similar calculation procedures. For example, the heat release rate per unit area of a burning material under the exposure and heat loss condition accounted for in equation 6 can be estimated by

$$\dot{q}_r'' = \dot{m}'' \Delta H_c \tag{7}$$

where

q_r''	=	heat release rate
H_c	=	effective heat of combustion

Similarly, release rates of smoke and toxic gases can be predicted from the expression:

$$\dot{m}_n = \psi_n \dot{m}'' \tag{8}$$

where

m_n''	=	mass loss production rate of species n
ψ_n	=	yield of species n

The yields of species are determined by small-scale testing. The smoke production rate of a simple quasi-steady fire can be estimated by accounting for the fraction of fuel converted to particulate. Since these quantities are difficult to measure independently, they are combined and reported as specific extinction area or in older fire literature as mass optical density.

These simple expressions describe the burning behavior of steady or quasi-steady fires. Examples of such fires are liquid and thermoplastic fuels which do not form char and fires of consistent area. In principle these expressions will describe environmental effects such as oxygen depletion, enhanced radiation, burning in ventilated atmospheres, etc., provided the dependence of a given parameter on the appropriate environmental condition can be calculated or measured, and the appropriate material characteristics are known.

3. Flame Spread

For most materials of practical interest the area of the fire is not constant. The material is ignited and the area of burning increases as the flame spreads across the surface. Equation 9 provides a means of measuring lateral flame spread velocity, based on work by Quintiere (1984). Equation 9 is expressed as the following:

$$V^{-1/2} = C\left[\dot{q}''_{o,ig} - \dot{q}''(x) \cdot F(t)\right] \quad (9)$$

where

V	=	flame spread velocity,
C	=	empirical constant from LIFT,
$q''_{o,ig}$	=	minimum ignition flux,
$q''(x)$	=	applied external heat flux, and
F(t)	=	function describing surface heat losses.

As discussed in Section 3.2.2, C and $q''_{o,ig}$ are measured in the LIFT flame spread apparatus. The use of the simple model for flame spread enables one to estimate the time dependence of the burning rate as the involved area of a material changes. The primary environmental variable accounted for in this expression is the external flux to the material.

C. APPLICATION OF SMALL-SCALE TEST METHODS

Consistent with the previous discussion and the simplified (but state-of-the-art) description of material burning behavior and its relationship to hazard assessment, this section develops the basic data required from two specific testing procedures, the cone calorimeter and the IMO/LIFT flame spread apparatus.

1. Modeling Parameters to be Derived From the Cone Calorimeter

The cone calorimeter is capable of providing data required for modeling the performance of materials in their end use configuration. While it must be remembered that the prediction of full-scale performance of materials from small-scale tests always involves extrapolations which may not be valid universally, the cone calorimeter overcomes many of the difficulties inherent with small-scale tests due to radiation. Nonetheless, there may be some variations in species and smoke yields, though no serious difficulties have been observed in the small number of experiments designed to find such difficulties.

The cone calorimeter is capable of generating modeling parameters for ignition, gasification, and the generation of heat, gaseous species, and smoke. It is important to note that modeling parameters for all these phenomena can be determined in the same experiments. Procedures for the generation of material fire properties relevant to fire and hazard modeling for each area will be derived in turn. In general, the simplest available methods will be described. More complex methods are available and could be employed depending on the ultimate degree of precision required.

a. Ignition

While the cone calorimeter is normally run with a spark ignitor just above the sample, the following procedures can be used for both piloted and spontaneous ignition tests. These procedures have not been used for spontaneous ignition studies, but the underlying modeling principles have been successfully applied to both piloted and spontaneous ignition. In general, piloted ignition behavior is more important because it is generally not possible to fully eliminate contact between the sample and any flame, spark, or ember from other fire sources.

The methods described here were originally utilized by Quintiere and Harkleroad (1984) in the LIFT flame spread apparatus. Their model of ignition assumes that the material is thermally thick and that heat losses from the sample may be ignored. The material is assumed to heat as a black inert material with constant thermal properties. Given these assumptions the surface temperature, T_s, is given by

$$T_s - T_o = \frac{2\sqrt{t}}{\sqrt{\pi k \rho c}} \dot{q}_l \qquad (10)$$

where

T_s = surface temperature,
T_o = initial temperature,
t = time,
k = mathematical thermal conductivity,
ρ = material density,
c = material heat capacity, and
q''_l = incident heat flux.

This expression is taken to hold up to the surface ignition temperature and for all fluxes sufficient to ignite the material; that is, for incident heat fluxes in excess of the critical radiant flux for ignition, $q''_{ign,min}$.

The critical radiant flux for ignition is determined by a bracketing procedure. The highest heat flux which does not cause ignition must be found. The usual test duration for such determinations is 30 minutes, though ignitions have been known to have occurred at times in excess of one hour, even for charring materials.

The ignition temperature may be defined by the critical radiant heat flux. Ignition at the critical flux occurs under steady state heat transfer conditions. As such, we can write a steady state heat balance at the critical heat flux:

$$\dot{q}''_{ign,min} = h_c (T_{s,ig} - T_o) + \sigma (T^4_{s,ig} - T^4_o) \quad (11)$$

$$= h (T_{s,ig} - T_o) \quad (12)$$

where $T_{s,ig}$ is the surface temperature at ignition, h_c is the convective heat transfer coefficient, and h is an overall heat transfer coefficient. The convective heat transfer coefficient for a 10 cm upward facing horizontal surface is approximately 10 W/m^2K and approximately 15 for a similar vertical surface. Fortunately, at ignition temperatures, radiative processes dominate so a precise h_c is not needed. Using equation 12 in equation 10 yields

$$\frac{\dot{q}''_{ig,min}}{\dot{q}''_l} = \left[\frac{4h^2 t_{ig}}{\pi k\rho c}\right]^{1/2} \quad (13)$$

Plotting the ignition data on a plot of $q''_{ig,min}/q''_l$ versus $\sqrt{t_{ig}}$ yields a straight line of slope, b. According to equation 13, this can be used to find the effective thermal inertia of the material, $k\rho c$, by the following:

$$k\rho c = \frac{4}{\pi} (h/b)^2 \quad (14)$$

Having determined the ignition temperature and the effective thermal inertia, equation 10 can be rearranged to find the time to ignition under a constant incident heat flux.

$$t_{ig} = \left[\frac{T_{ig} - T_o}{2\dot{q}''_l}\right] \pi k\rho c \quad (15)$$

Under variable incident heat fluxes the ignition time is defined by the following:

$$\int_o^{t_{ig}} \frac{\dot{q}''_l}{\sqrt{t}}\, dt = (T_{ig} - T_o) \sqrt{\frac{\pi k\rho c}{8}} \quad (16)$$

Because heat losses are ignored in this model, it is possible for a variable heat flux less than the critical heat flux to "ignite" the sample according to equation 16. Any ignition time found for a flux less than the critical flux should be viewed as an underestimate.

In summary, the ignition temperature, the critical radiant heat flux for ignition, and the effective thermal inertia can be determined from the cone calorimeter. The critical radiant heat flux for ignition is determined experimentally by bracketing. The accuracy of the determination is directly related to the number of tests performed in the bracketing procedure. The ignition temperature can be determined using the critical radiant heat flux for ignition in equation 11. By performing a series of experiments at fluxes above the critical radiant heat flux for ignition a plot of $q''_{ig,min}/q''_{I}$ versus $\sqrt{t_{ig}}$ can be constructed. The slope, b, of the straight line is used in equation 14 to define the effective thermal inertia. Having determined the ignition temperature and the effective thermal inertia, equation 15 and 16 can be used to predict the time to ignition and if ignition will occur at all.

b. Heat of Gasification

The heat of gasification is defined by the expression

$$\dot{G}_f'' = (\dot{q}_I'' - \dot{q}_L'')/\Delta H_g \qquad (17)$$

where G''_f is the mass loss rate and q''_L is the heat loss from the sample. The heat of gasification is a means of relating the fuel gasification rate to the heat absorbed by the sample without resorting to a detailed heat transfer and kinetics calculation in the sample.

While the ratio of the heat absorbed to the mass of fuel gasified is a constant for steady burning of a liquid, in general the heat of gasification is a function of the progress of the decomposition process. Several investigators have made attempts to develop a method of expressing the heat of gasification as a function of a single progress variable. The choices of progress variables include the total heat released, the total mass released, or the total energy absorbed up to the point in time under consideration. Clearly, all of these progress variables are closely related. The most direct and most studied progress variable is the total energy absorbed. This variable relates directly to the state of the remaining sample and in principle can respond to differences in the heat lost to the environment. It has been shown that this method will work for charring and noncharring solids of various thicknesses, for both constant and linearly increasing heat flux histories.

The total heat absorbed by a sample, q", is given by

$$q'' = \int_o^t (\dot{q}_I'' - \dot{q}_L'')\, dt \qquad (18)$$

As a simple first order procedure, assume that the heat losses are zero during the pre-ignition stage and are constant during burning. Rear face heat losses will be minimized by backing the sample with a low density insulating board. It is well known that the surface temperature is nearly constant during burning. After conducting experiments over a range of incident heat fluxes, the heat losses from the surface can be found by plotting

the maximum mass loss rate versus the incident heat flux. According to equation 17, the slope of the resulting curve is the minimum heat of gasification and the intercept is the constant surface heat loss, q''_L.

With q''_L known, it is now possible to process all the mass loss rate data. From Equation 18:

$$\Delta H_g (q'') = \frac{\dot{q}''_I - \dot{q}''_L}{\dot{G}''_f (q'')} \tag{19}$$

This expression applied to the mass loss data yields the heat of gasification as a function of the total heat absorbed. Further work is required to develop models of $\Delta_g(q'')$ for different classes of materials so that the function $\Delta_g(q'')$ can be described parametrically.

Having determined $\Delta_g(q'')$ and q''_L, the mass loss rate from a sample can be determined from

$$\dot{G}''_f = \frac{\dot{q}''_I (t) - \dot{q}''_L (t)}{\Delta H_g (q'')} \tag{20}$$

This along with the heat of combustion are used to determine the heat release.

c. Generation of Heat, Gaseous Species, and Smoke

Given the fuel volatilization rate, it is straightforward to determine the heat release rate, the generation rate of gaseous species, and smoke. These quantities are related to the mass loss rate through the following:

$$\Delta H_c = \frac{\dot{q}}{\dot{G}_f} \tag{21}$$

$$\Phi_I = \frac{\dot{G}_I}{\dot{G}_f} = \frac{Y_{I,exit} \dot{m}_{exit}}{\dot{G}_f} \tag{22}$$

$$\sigma_m = \frac{k_{exit} \dot{m}_{exit}}{\dot{G}_{L,exit}} \tag{23}$$

where G_f is the mass loss rate, q is the heat release rate measured by oxygen calorimetry, $Y_{i;exh}$ is the mass fraction of species i in the exhaust, m_{exh} is the measured exhaust rate, k_{ext} is the measured extinction coefficient in the exhaust, and $_{exh}$ is the measured gas density in the exhaust. ΔH_c, ψ_i, and σ_m can be determined as average values or as functions of the total energy absorbed, q". These values can then be used in hazard analysis procedures.

2. Modeling Parameters to be Derived From the LIFT/IMO Apparatus

The LIFT/IMO apparatus is capable of defining the minimum surface temperature and minimum incident heat flux required for lateral or downward flame spread as well as the flame spread modulus. The basic equation for lateral flame spread is

$$V = \frac{\phi}{k\rho c\,(T_{ig} - T_o)^2} \tag{24}$$

where V is the flame spread velocity, ϕ is the flame spread modulus, $k\rho c$ is the thermal inertia, T_{ig} is the sample ignition temperature, and T_o is the ambient temperature. This can be rewritten as

$$V^{-1/2} = c\left[\dot{q}''_{ig,min} - \dot{q}''_I\,F(t)\right] \tag{25}$$

F(t) is a function of the time and thermal properties of the material. Plotting $V^{-1/2}$ versus $q''_I F(t)$ yields a straight line with a slope, c, and an intercept, $q''_{ig;min}$. For accuracy and simplicity it is desirable to allow sufficient preheat time that $F(t)=1$. ϕ can be found from

$$\phi = \frac{4}{\pi c^2 b^2} \tag{26}$$

where b is the slope of the ignition plot.

The minimum external heat flux for flame spread, $q''_{e,min}$, is determined by the location at which the flame travel stops in the test. The surface temperature required for flame spread, $T_{s;min}$, can be determined from a steady state heat balance at that location.

$$\dot{q}''_{e,min} = h_c\,(T_{s,min} - T_o) + \sigma\,(T^4_{s,min} - T^4_o) \tag{27}$$

where $h_c = 15\ W/m^2\ K$.

The parameters σ, $T_{s,min}$, and $q''_{e,min}$ can be used to model the rate of lateral flame spread and hence the rate of heat release rate.

D. MODELING LIMITATIONS

The limitations of the approach described in this section are primarily related to limitations in the state-of-the-art of fire dynamics. There are limitations in the bench-scale test procedures but these are primarily related to the relatively simplified theories of burning to which they are related.

The actual performance of these small-scale test methods in predicting full-scale behavior is discussed in the next section.

4.0 SMALL-SCALE FLAMMABILITY TESTS AND FULL-SCALE FIRE PERFORMANCE

This section summarizes the state-of-the-art relative to the ability of the cone calorimeter and LIFT flame spread apparatus to provide data which can be related to full-scale behavior. As an indication of generic problems associated with existing test methods, the following two examples are provided. These are not specifically Navy materials.

Cleary and Quintiere (1991) have done extensive small-scale testing with foam plastics. They have grouped their results in two tables which present selected small-scale data reflecting various aspects of their fire performance as well as inherent material property. The materials are grouped as Class I and Class II as determined by the ASTM E 84 Tunnel Test, where to qualify for Type I, the material must achieve a Flame Spread Index (FSI) of less than 25 and a smoke rating of no greater than 450. The most inconsistent observation is the variation of the peak heat release rate for the material in each class. In Class I, there is a factor of 4.2 disparity between the highest and the lowest peak heat release rate as measured at 50 kW/m^2 irradiance in the cone calorimeter. Translated to real-scale fire performance, this is an unacceptable range of minimum surface areas required for room flashover. The minimum heat flux (kW/m^2) for flame spread, as measured in the LIFT test, also reflects this disparity as $q_{S,MIN}"$ ranges from 6.0 to 28.0 kW/m^2 a factor of 4.7. Similarly for Class II, there is a factor of 4.1 range for the minimum heat flux for flame spread and a factor of 2.5 for the measured peak heat release rate. These data are summarized in Table 3 for flame spread less than 25 and Table 4 for flame spread greater than 25 by material.

Belles, *et al.* have also investigated the relationship between ASTM E 84 Tunnel Test and heat release data from ASTM Room/Corner Test Method. The ASTM Room/Corner Test Method can be used to calculate the heat release rate of a material based upon oxygen depletion calorimetry. As can be seen from Table 5, there is a factor of 28 disparity between 100% nylon (R) and 100% polyester (Q) heat release rates both of which have an ASTM E 84 flame spread rating of 15. This figure emphasizes the fact that ASTM E 84 flame spread ratings are not indicative of the flashover potential in a room fire nor the material's rate of heat release and more importantly, that heat release rate properties more directly relate to full-scale performance.

Table 3. Class I Flame Spread Materials, FSI < 25
[Cleary and Quintiere (1991)]

	Q_{PEAK}	H_c	$q_{LIFT,MIN}''$
Rigid Polyurethane Foam Spray, 2.4 lb/ft² #1	331	10.9	6.0
Rigid Polyurethane Foam Spray, 2.4 lb/ft² #2	165	11.0	6.6
Rigid Polyurethane Panel Foam, 2.6 lb/ft²	147	10.0	7.7
Polyisocyanurate Foam Board, 1.6 lb/ft²	79	9.1	10.8
Phenolic Foam, 2.6 lb/ft²	111	14.2	28.0

Q_{PEAK} The peak heat release (kW/m²) rate as measured in the standard cone calorimeter test at an irradiance of 50 kW/m².

H_c Heat of combustion (kJ/g) as measured in the standard cone calorimeter test at an irradiance of 50 kW/m².

$q_{LIFT,MIN}''$ Minimum heat flux (kW/m²) for flame spread as measured in the standard LIFT test.

Table 4. Class II Flame Spread Materials, FSI > 25
[Cleary and Quintiere (1991)]

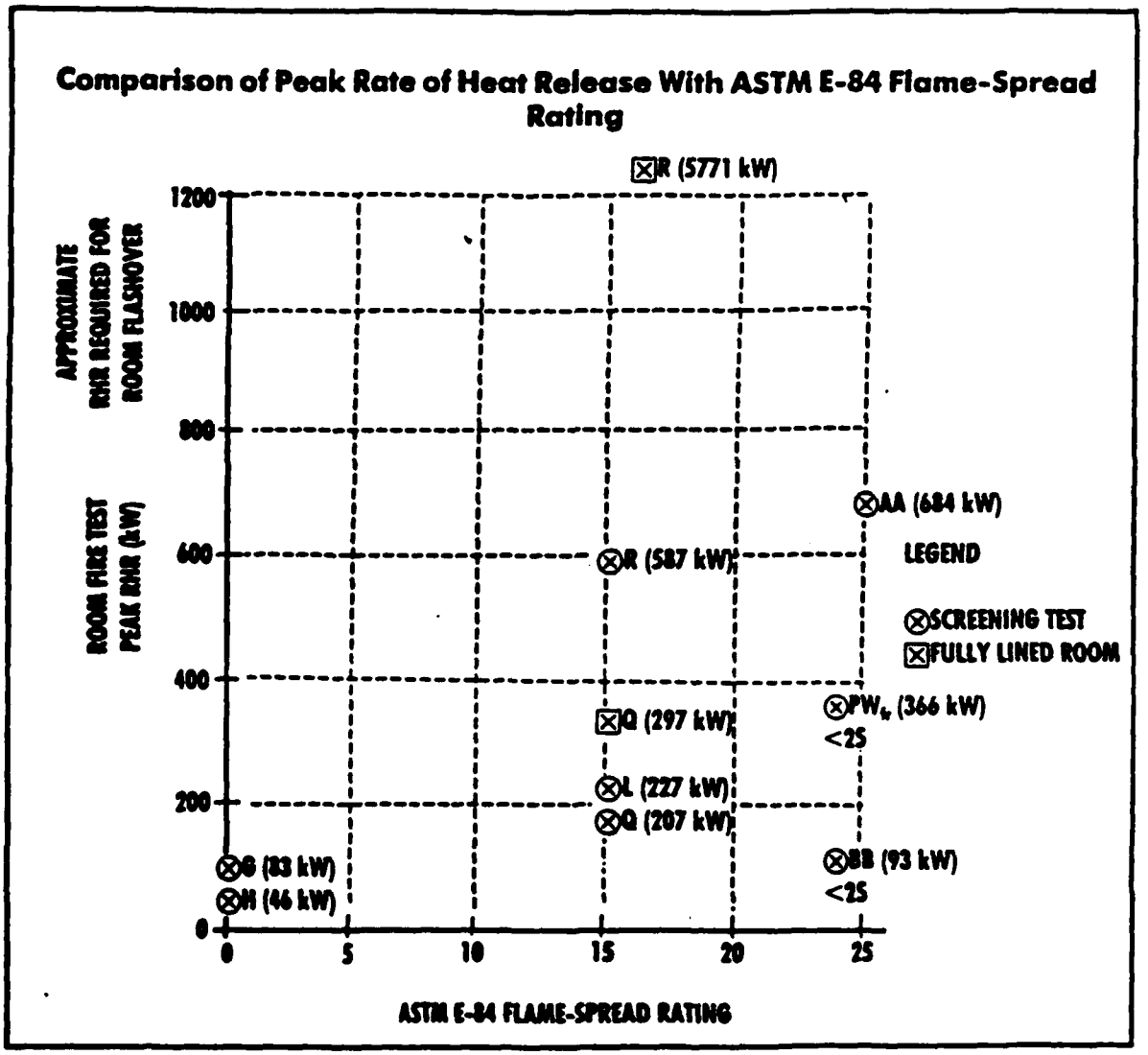
	Q_{PEAK}	H_c	$q_{ig,MIN}''$
Fire Retardant Expanded Polystyrene Foam, 1 lb/ft³	694	34.5	3.7
Non-fire Retardant Expanded Polystyrene Foam, 1 lb/ft³	886	32.0	<1.0
Fire Retardant Expanded Polystyrene Foam, 2 lb/ft³	734	30.4	2.9
Fire Retardant Extruded Polystyrene Foam, 2 lb/ft³	610	29.3	2.7
Non-fire Retardant Rigid Polyurethane Foam Spray, 3.2 lb/ft³	361	19.6	0.9

Q_{PEAK} The peak heat release (kW/m²) rate as measured in the standard cone calorimeter test at an irradiance of 50 kW/m².

H_c Heat of combustion (kJ/g) as measured in the standard cone calorimeter test at an irradiance of 50 kW/m².

$q_{ig,MIN}''$ Minimum heat flux (kW/m²) for flame spread as measured in the standard LIFT test.

Table 5. Relationship Between Heat Release Rate and Flame (ASTM E-84) [Heiss, et al. (1968)]



The prediction of full-scale fire behavior from small-scale test data is relatively new; therefore, it is often more a question of the ability to apply the experimental data through theoretical relationships which account for the difficult burning environments than a question of the apparatus' ability to collect useful data.

The following measurements are available from the cone calorimeter and have been used previously in the effort to model real-scale fire performance: ignitability (the time to ignition at a specified irradiance), heat release rate per unit area, CO (carbon monoxide) gas yield, CO_2 (carbon dioxide) gas yield, HCN (hydrogen cyanide) gas yield, HCl (hydrogen chloride) gas yield, and smoke production rate. What follows is a presentation of results of various attempts to use cone calorimeter data to model real-scale fire performance and the relative success or failure thereof.

4.1 Ignition

Ignition of materials involves many considerations such issues as radiative versus convective heating and piloted versus auto ignition; however, the issue of concern here is scalability. There has been very little work done addressing this question. Östman and Nussbaum (1989) tried to correlate time to ignition at 25 kW/m^2 exposure in the cone calorimeter with time to flashover as measured in the full-scale room fire tests. Their effort showed no correlation as reflected in Fig. 8. This finding is not particularly disturbing since flashover is a strong function of heat release rate. Such correlation is indeed found when heat release rate of the material is integrated into the correlation.

Wong *et al.* (1990) through a composite testing program have some interesting results. Their work has shown that the LIFT ignition delay data found in Table 6 are reflected in large-scale observation. These results apply directly to the Navy's use of composites.

Test 3 exposed unfaced GRP to 15 kW/m^2 for twenty minutes without ignition. LIFT data shows no ignition at 15.0 kW/m^2. Test 8 exposed phenolic-faced GRP to 45 kW/m^2 for five minutes where the LIFT data indicates no probable ignition before 325 seconds at 40 kW/m^2 exposure. Similarly, in Test 9, phenolic-faced GRP was exposed to 32 kW/m^2 with spikes to 50 kW/m^2 for five minutes and again no ignition was obtained. LIFT data indicates 370 seconds of 35 kW/m^2 exposure before ignition. Test summaries can be found for these three tests in Tables 7 through 9.

Janssens (1991) has obtained excellent correlation between a theoretical ignition model and cone calorimeter ignition delay times across a wide range of wood materials and exposure heat flux levels. Atreya and Abu-Zaid (1991) have developed a theoretical ignition model which includes the effects of moisture content, air velocity, and oxygen concentration. The model successfully predicts material ignition behavior under a radiant heater (cone).

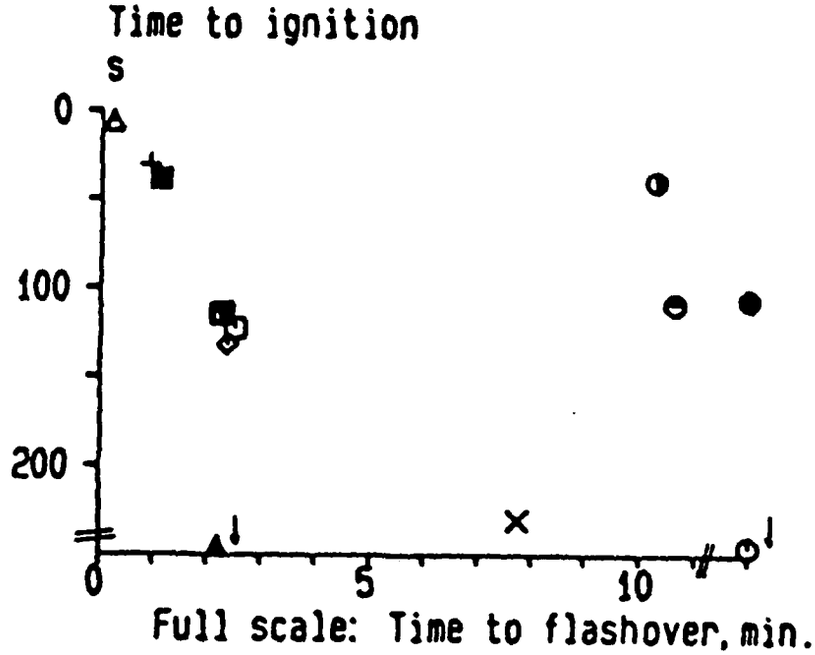


Fig. 8 - Ignition time vs. full-scale time to flashover
[Ostman and Nussbaum (1989)]

Table 6. Ignition Times for Faced and Unfaced Glass Reinforced Polyester Subjected to Various Levels of External Flux [Wong et al. (1990)]

Composite	External Flux (kW/m^2)	Ignition Delay Time (Sec)
Unfaced GRP	15.0	No ignition
	18.2	995
	20.0	903
	24.5	330
	30.0	120
	45.0	63
Phenolic Faced GRP	20.0	838 (edge ignition)
	24.7	610
	30.4	570
	35.0	370
	40.0	325
	50.0	201
	58.5	145

Table 7. Composite Module Fire Test Summary Data Sheet [Wong et al. (1990)]

TEST: 3 COMPOSITE MATERIAL: Polyester DATE OF TEST: 7/18/89

FIRE SIZE: 200 kW

FIRE LOCATION: Southeast corner of the east compartment, 24 in. (61 cm) away from both the south and east walls. The intent was to provide, as close as possible, a flux at or just below the critical flux for ignition at the walls.

DURATION OF EXPOSURE FIRE: 20 min

FIRE COMPARTMENT AIR TEMPERATURE (°C)
MAXIMUM OVERHEAD TEMPERATURE: 330
AVERAGE UPPER LAYER TEMPERATURE: 280

SURFACE FLAME SPREAD TEMPERATURES (°C): N/A

OVERHEAD SURFACE TEMPERATURES (°C):
Exposed 280
Unexposed 140

TOTAL HEAT FLUX TO EXPOSED SURFACE (kW/m^2)
LOW (15 in., 41 cm) 15
HIGH (63 in., 160 cm) 15

ADJACENT COMPARTMENT TEMPERATURE (°C)
MAXIMUM OVERHEAD AIR TEMPERATURE: 60

HEAT TRANSFER THROUGH DIVISIONAL BULKHEAD: (7 ft, 213 cm level)
Exposed 190°C
Unexposed 115°C

SEQUENCE OF EVENTS (FROM TIME 0:00 IGNITION):

0:00	Ignition
2:00	Flames from the burner almost to the overhead, then steadied out to 6 ft (183 cm) above the deck
3:10	Smoke layer 4 ft (122 cm) down from the overhead
6:00	Smoke layer 5.5 ft (168 cm) down from the overhead
7:20	Unexposed surface of Frame Bays 6 and 8 starting to discolor (whitening)
20:00	Fuel shut off; no ignition of any surface observed (IR camera used to view surfaces immediately after the fuel was shut down). No water was used.

Table 8. Composite Module Fire Test Summary Data Sheet [Wong et al. (1990)]

TEST: 8 COMPOSITE MATERIAL: Phenolic coated polyester DATE OF TEST: 7-24-89

FIRE SIZE: 50 kW

FIRE LOCATION: East compartment, against South wall, Frame Bay 8

DURATION OF EXPOSURE FIRE: 5 min

FIRE COMPARTMENT AIR TEMPERATURE (°C)
MAXIMUM OVERHEAD TEMPERATURE: 155
AVERAGE UPPER LAYER TEMPERATURE: 100

SURFACE FLAME SPREAD TEMPERATURES (°C):
Lowest T/C (1 ft (30 cm)) above deck 300°C,
(1.5 ft (46 cm)) 400°C

TOTAL HEAT FLUX TO EXPOSED SURFACE (kW/m^2)
LOW (15 in., 41 cm): 45 (NIST Lift data indicate no
HIGH (63 in., 160 cm): 5 ignition probable before
325 s at 40 kW/m^2)

ADJACENT COMPARTMENT TEMPERATURE (°C)
MAXIMUM OVERHEAD AIR TEMPERATURE: 40

HEAT TRANSFER THROUGH DIVISIONAL BULKHEAD: N/A

SEQUENCE OF EVENTS (FROM TIME 0:00 IGNITION):
0:00 Ignition
2:45 50-60°C backside (unexposed) temp
3:06 Very light smoke
5:00 Fuel off
5:30 No flame on bulkhead, small flames on burner

ASSESSMENT OF DAMAGE:
1. No charring evident; cured the material a little bit, e.g., differential cure, blackened area could be wiped clean to a glazed surface.
2. The fire damage/burn pattern could not be seen on the unexposed side.
3. There was no sustained burning on the wall.
4. No debonding of the phenolic and the GRP.

Table 9. Composite Module Fire Test Summary Data Sheet [Wong et al. (1990)]

TEST: 9 COMPOSITE MATERIAL: Phenolic coated polyester DATE OF TEST: 7-24-89

FIRE SIZE: 50 kW

FIRE LOCATION: East compartment, against southeast corner, Frame Bay 7

DURATION OF EXPOSURE FIRE: 5 min

FIRE COMPARTMENT AIR TEMPERATURE (°C)
MAXIMUM OVERHEAD TEMPERATURE: 140
AVERAGE UPPER LAYER TEMPERATURE: 100

SURFACE FLAME SPREAD TEMPERATURES (°C):
Lowest T/C (1 ft (30 cm)) above deck reached max temp of 250°C

TOTAL HEAT FLUX TO EXPOSED SURFACE (kW/m^2)
LOW (15 in., 41 cm): 32 with spikes to 50
HIGH (63 in., 160 cm): 4

ADJACENT COMPARTMENT TEMPERATURE (°C)
MAXIMUM OVERHEAD AIR TEMPERATURE: 45

HEAT TRANSFER THROUGH DIVISIONAL BULKHEAD: N/A

SEQUENCE OF EVENTS (FROM TIME 0:00 IGNITION):

0:00	Ignition
2:05	Light smoke
3:10	A little smoke from the radiometer hole
5:00	Fuel off
5:22	Fire fighter in compartment, nothing burning in bulkheads

ASSESSMENT OF DAMAGE:

1. Flames extended to the 2 ft (61 cm) T-bar, and then deflected away. Fire leaned toward east wall.
2. Thermal analyzer saw hot bolts.
3. East wall lowest (2 ft (61 cm)) horizontal frame bay debonding of phenolic from polyester layers. No corner delamination at the boundary angle. No debonding evident in the lowest south wall frame bay.

Kanury (1988) has also done some investigation to ignition characterization. Although not in direct terms of ignition time, he has shown that the height of the sample impacts the required flux for auto-ignition. A order of magnitude change in the height can affect the required flux by a factor of two as seen in Fig. 9.

For cases where piloted ignition is the primary concern, a radiative heat source of variable power should be directly relatable to full-scale ignition behavior. This was seen dramatically in the Navy composite box testing. Flame spread is effectively a series of ignitions of unessential(?) areas of a sample. Hence, an evaluation of the ability of small-scale methods to predict flame spread is a de facto measure of their success in predicting ignition.

4.2 Full-Scale Heat Release Rates

The most important material property impacting fire growth and hence fire hazard is the rate of heat release of the material. The ability to relate small-scale measured heat release properties to the full-scale heat release rate of upholstered furniture or of a wall lining material is a critical test of the "scalability" of a test method.

A modest effort related at a few specific applications has been large body of work has been attributed to this effort, to model/predict full-scale heat release rates from bench-scale data [Braun, Shields, and Harris (1989); Cleary (1990); Cleary and Quintiere (1991a); Babrauskas and Wickström (1989); Parker *et al.* (1991); Cleary and Quintiere (1991b); Karlsson (1991); Babrauskas *et al.* (1988); Babrauskas and Krasny (1985); Babrauskas (1986)]. This work has been very successful, demonstrating that it is very feasible to model full-scale heat release rates. The majority of the work has been performed on wall lining material [Cleary (1990); Cleary and Quintiere (1991a); Babrauskas and Wickström (1989); Cleary and Quintiere (1991b); Karlsson (1991); Babrauskas *et al.* (1988)] and on upholstered furniture [Babrauskas and Wickström (1989); Parker *et al.* (1991); Babrauskas (1984); Babrauskas and Krasny (1985); Ames and Rogers (1990)]. Both the wall linings method and upholstered furniture require manipulation of cone calorimeter data in an algebraic equation which utilizes other parameters that further characterize and distinguish the test specimen. The correlation used to scale furniture test data has four factors: fabric factor, padding factor, frame factor, and style factor. The correlations with scale wall lining materials used only a flame heating parameter which is obtained from the LIFT apparatus according to ASTM E1321. These correlations have proved very successful in making accurate real-scale heat release rate predictions.

4.3 Full-Scale Room Flashover for Surface Linings

Three distinct areas of efforts have been made in the attempt to predict full-scale room flashover for surface linings. The most basic is a simple empirical correlation between measurable parameters in small and full-scale [Östman and Nussbaum (1989)]. Another area pursued was a physical correlation which incorporates some basic phenomenological effects and small-scale data [Babrauskas (1984)]. Mathematical

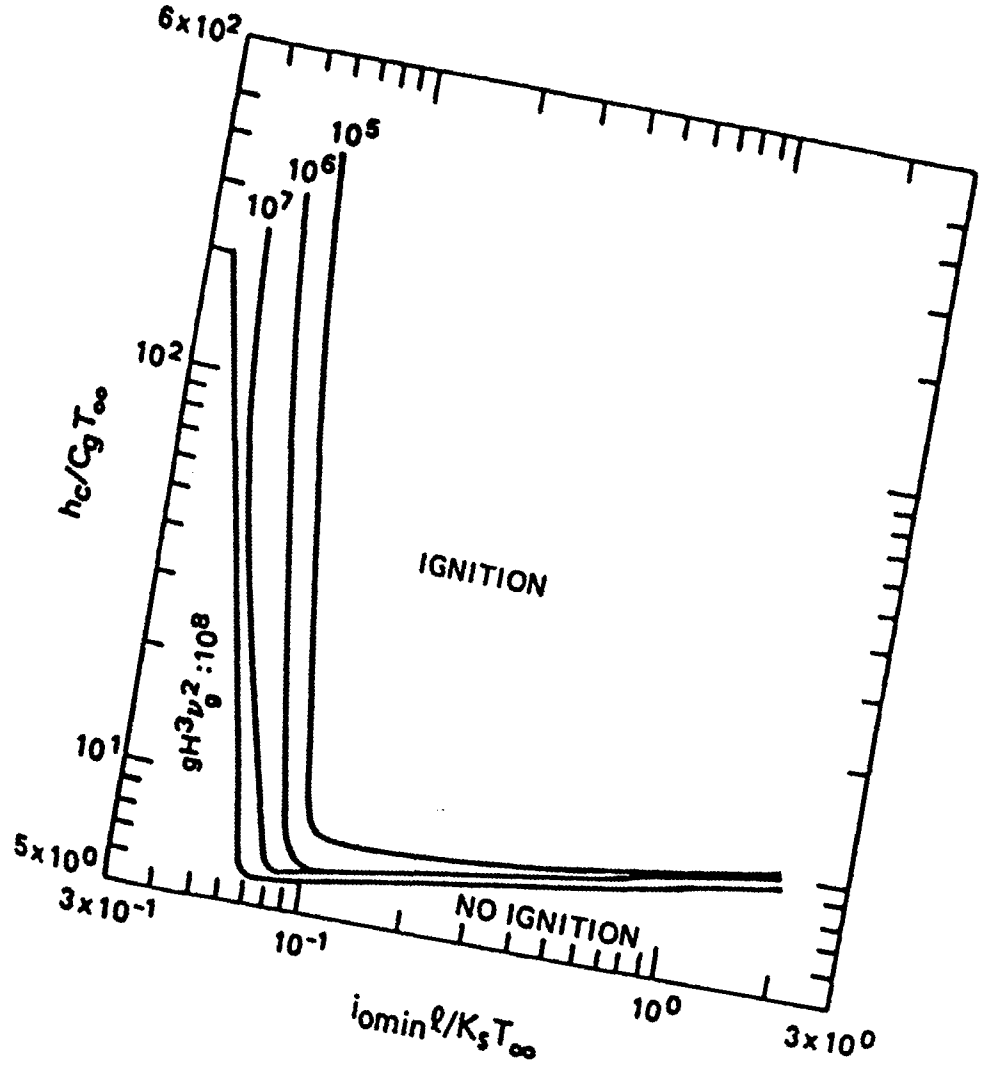


Fig. 9 - Influence of plate height on threshold flux [Kanury (1988)]

models have also been developed [Magnusson and Sundström (1985); Wickström and Göronsson (1987)].

The simple empirical correlation [Östman and Nussbaum (1989)] was found to be quite valid for 11 lining materials which resulted in flashover full-scale. Materials ranged from paper and textile covered gypsum board to rigid polymethane foam. Figure 10 presents the best correlation that was found between the small-scale rate of heat release parameter and the full-scale time to flashover. The relation which was used is

$$T = a \times \frac{t \cdot \sqrt{\rho}}{A} + b \qquad (28)$$

where
- T = time to flashover full scale, s;
- t = time to ignition small scale @ 25 kW/m^2, s;
- A = heat release during peak period @ 50 kW/m^2, J/m^2;
- ρ = density of material, kg/m^3;
- a = constant, 2.76 x 10^6, J·(kg·m)$^{-0.5}$; and
- b = constant, -46.0 s.

A more physical correlation has been developed [Babrauskas (1984)]. This correlation presumes that there is a relationship between the square root of the ceiling area divided by the time to reach flashover full-scale tests and the bench-scale heat release rates divided by the time to ignition. The bench-scale heat release rate is taken to be a 60 second average for specimens exposed at 25 kW/m^2. The results here show a fair correlation as demonstrated in Fig. 11. The data that were used for Fig. 11 can be found in Table 8. It is noted that this method had difficulty dealing with different strengths of ignition burners in the full-scale tests as this led to substantial variations in flashover times for the same material.

An excellent correlation of time to flashover versus bench-scale ignition and heat release rate data was obtained by Karlsson and Magnusson (1991). Figure 12 summarizes the correlation of on the order of 100 full-scale tests.

4.4 Flame Spread on Interior Finishes

The area of most current active development relative to the use of small-scale test results is in the prediction of flame spread on interior finish. There are at least five interdependent approaches to this problem. They all include the use of small-scale ignition and heat release rate data coupled with a theoretical method to predict flame spread and full-scale heat release properties. At least one method [Quintiere and Cleary (1991)] uses results of the LIFT flame spread apparatus.

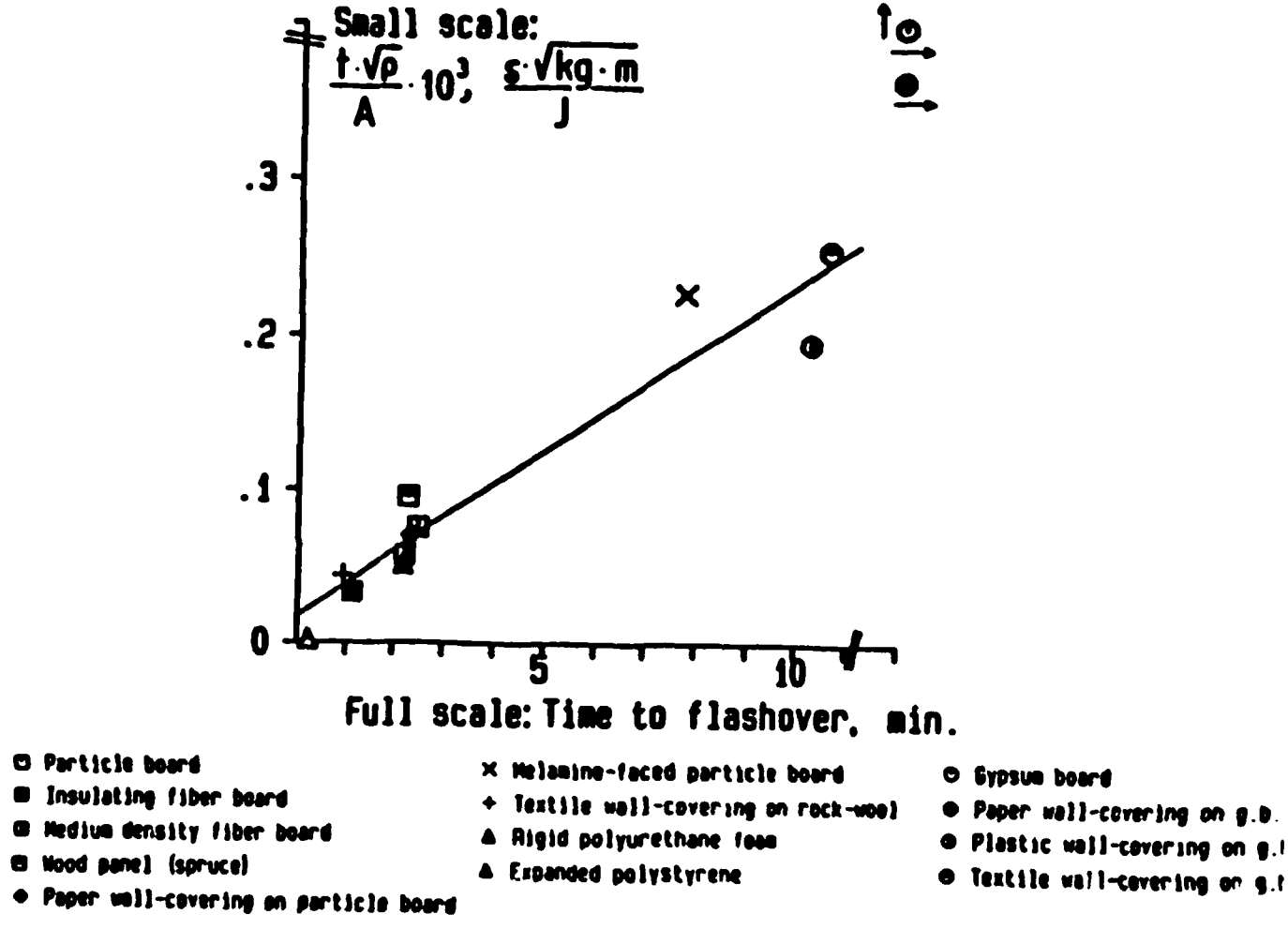


Fig. 10 - Small-scale heat release rate parameter vs. full-scale time to flashover [Ostman and Nussbaum (1989)]

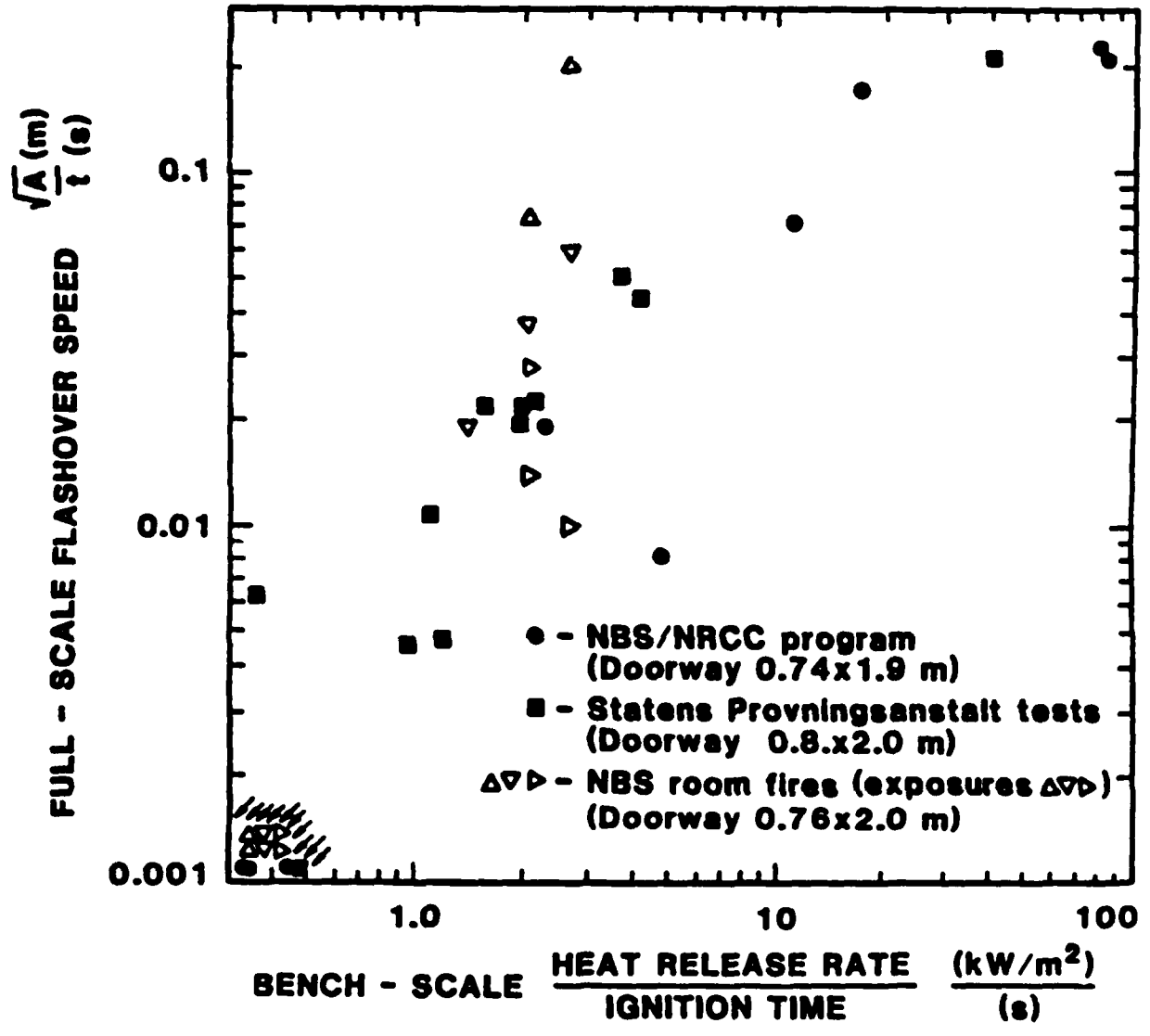


Fig. 11 - Full-scale flashover speed vs. bench-scale heat release rate parameter [Babrauskas (1984)]

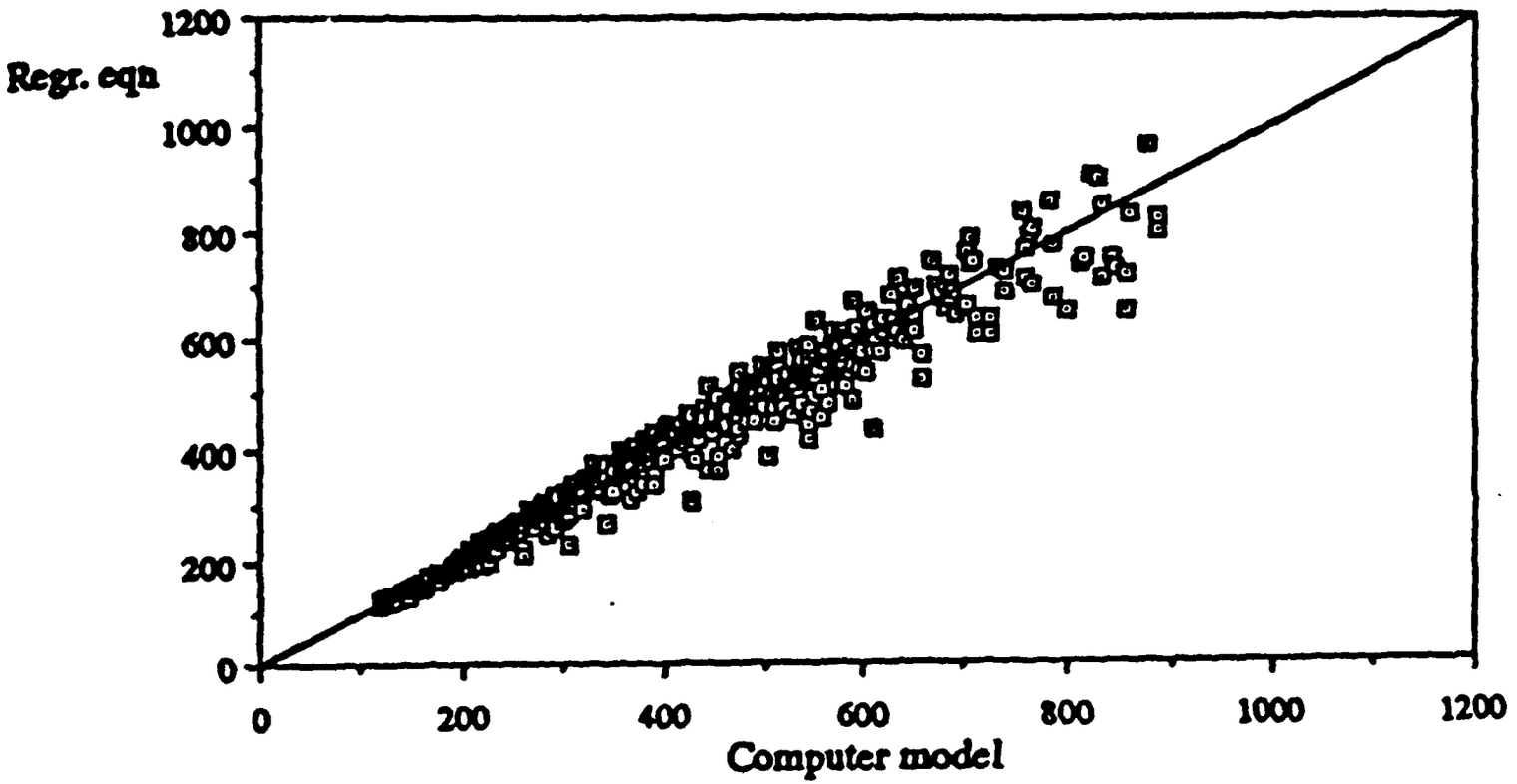


Fig. 12 - Time to flashover, model vs. regression equation [Karlsson and Magnusson (1991)]

The theoretical approaches used vary widely in their level of detail. The most attractive, from the standpoint of simplexity in using small-scale data, is that of Quintiere and Cleary (1991), Saito *et al.* (1986), and Mowrer and Williamson (1991). This approach involves substantial simplification of governing equations and yields two critical flammability parameters, obtained from bench-scale cone calorimeter data defined as follows [Cleary and Quintiere (1991)]:

$$a = k_f \dot{Q}'' - 1$$

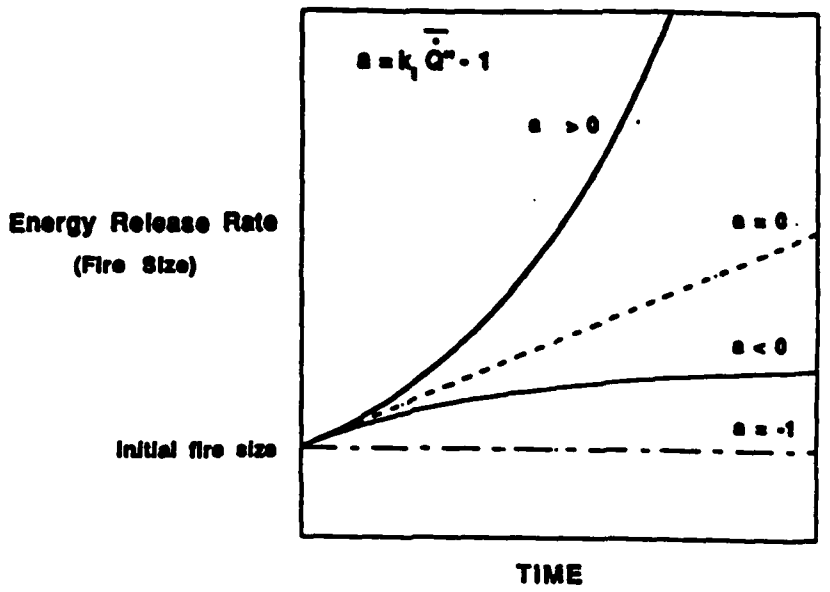
$$b = a - t_{ig} / t_B$$

where k_f = constant approximately equal to 0.01 m^2/kW for upward flame spread;
Q'' = peak average heat release rate (kW/m^2);
t_B = burn time associated with peak value (sec); and
t_{ig} = time to ignition (sec).
Q'', t_{ig}, and t_B are evaluated using bench-scale methods at the appropriate exposure flux.

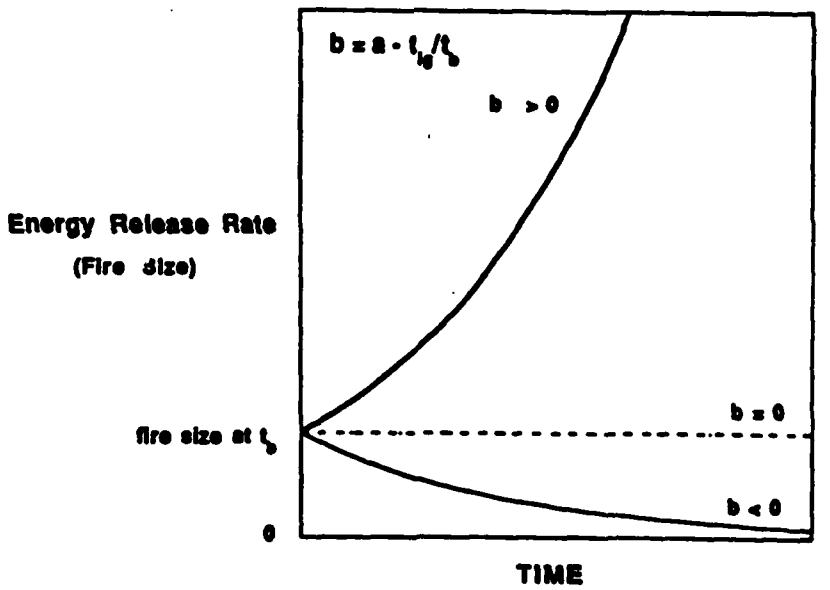
The importance of these parameters can be seen in Fig. 13. For values of $a>0$ and $b>0$, the fire growth rate accelerates; for $a=0$, $b=0$, the fire does not spread below the initial fire size. This simplification, if found to hold, has tremendous implications for specifying material flammability properties relative to flame spread. The small-scale parameters, Q'', t_{ig} and t_B, relate directly to full-scale performance and performance objectives, "e.g. a small-scale fire will not grow large."

The validity of this approach is more problematic. The method has been correlated with reasonable success against a range of interior finish materials in a wall/corner geometry. Figures 14 and 15 illustrate the range of agreement. Table 10 summarizes the relationship between the experimental (full-scale) measured time to reach 1000 kW versus model calculations under varying assumptions of external heat flux and/or surface temperature. Table 11 provides experimental and model predictions on time to peak and peak heat release rates for textile wall coverings.

Another promising approach is that taken by Delichatsios *et al.* (1991) and Delichatsios and Saito (1991). The model here is slightly more complex, but the bench-scale flammability data are used to predict full-scale flame spread performance. Again, small-scale ignition and heat release rate data are used. Additional thermophysical data required are inferred from the bench-scale data. Both charring and non-charring materials have been tested. Good agreement is obtained between the model predictions (based on bench-scale data) and full-scale experiments.



Dependence of Fire Growth Potential on (a) Parameter



Dependence of Fire Growth Potential on (b) Parameter

Fig. 13 - Energy release rates vs. time; the dependence of fire growth potential on two parameters [Cleary and Quintiere (1991)]

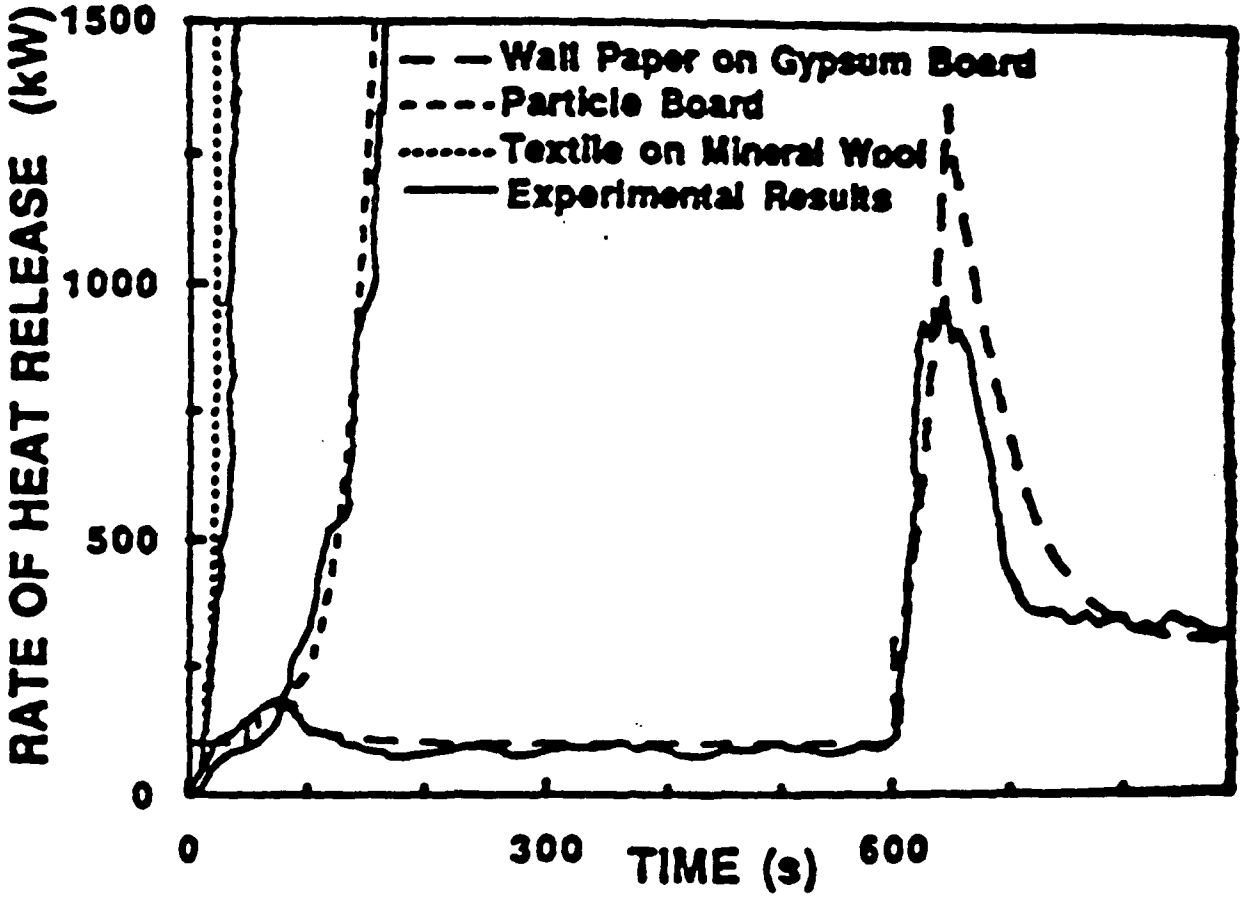


Fig. 14 - Heat release rate predictions for Swedish data (irradiance level = 25 kW/m²) [Cleary and Quintiere (1991)]

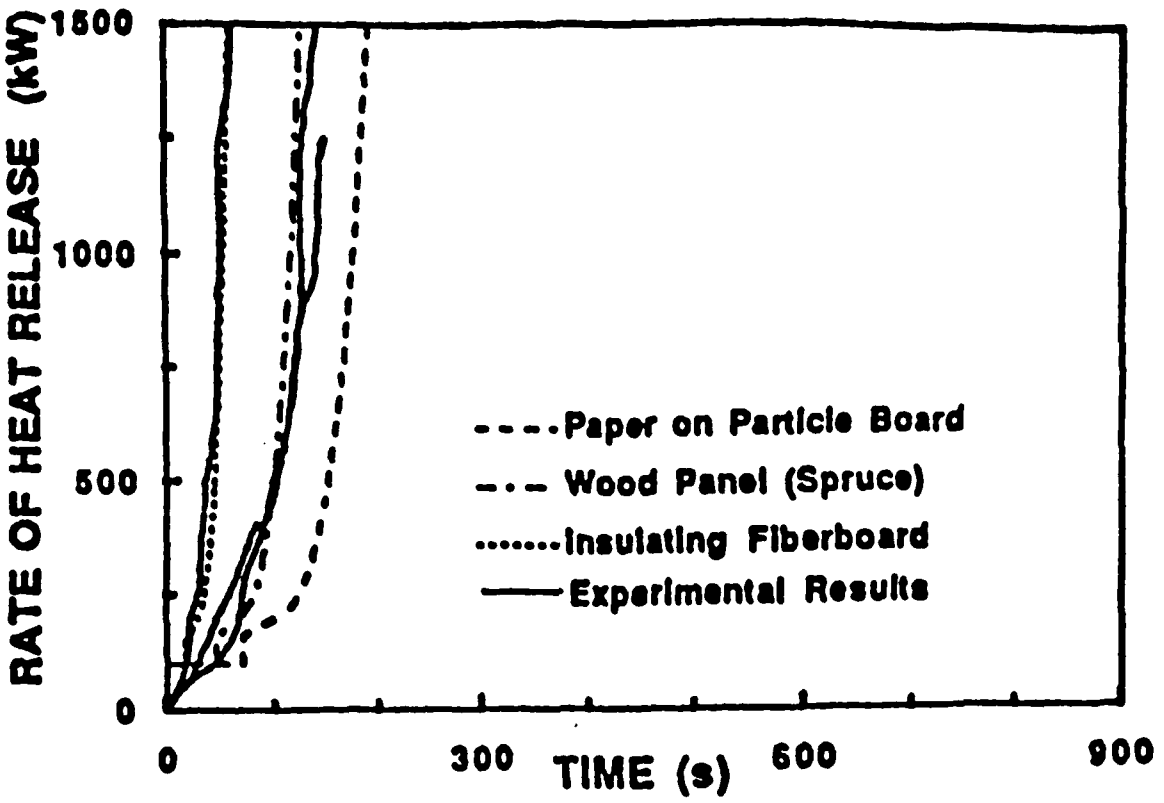


Fig. 15 - Heat release rate predictions for Swedish data (irradiance level = 25 kW/m²) [Cleary and Quintiere (1991)]

Table 10. Time to Achieve a 1 MW Fire for the Swedish Room Tests [Cleary and Quintiere (1991)]

Material	Experimental Time (s)	Model Calculations (25 kW/m²) (T_s - 25°C) (s)	(50 kW/m²) (T_s - 25°C) (s)	(25 kW/m²) (T_s - 80°C) (s)
Particle Board	157	198	143	145
Insulating Fiberboard	59	77	58	55
Medium Density Fiberboard	131	180	148	125
Wood Panel (Spruce)	131	165	143	117
Melamine on Particle Board	465	-	402	-
Wall Paper on Gypsum Board	640	632	616	641
PVC on Gypsum Board	611	619	606	622
Textile on Gypsum Board	639	615	613	615
Textile on Mineral Wool	43	33	28	24
Paper on Particle Board	143	237	220	177
Rigid Polyurethane Foam	6	11	6	7
Expanded Polystyrene Foam	115	-	122	-
Gypsum Board	*	-	*	-

\- Data were not taken
* Did not reach 1 MW

Table 11 Textile Wall Covering Room Fire Tests
[Cleary and Quintiere (1991)]

Material	Full Scale Screening Tests (0.31 m width) $\dot{Q}_p$ (kW)	t_p^* (s)	Full Scale Screening Tests (0.62 m width) $\dot{Q}_p$ (kW)	t_p^* (s)	Model Calculations $\dot{Q}_p$ (kW) (30 kW/m^2)	t_p^* (s)	$\dot{Q}_p$ (kW) (50 kW/m^2)	t_p^* (s)
(H) 85% wool 15% cotton	46	30	160	40	-		146	46
(C) 55% cotton 45% rayon	62	30	119	60	137	40	139	37
(G) 100% polyester	83	30	-		64	39	56	44
(B) 100% polyester	207	45	298	60	121	46	270	46
(Q) 100% polyester	207	40	480	40	145	50	293	55
(Qfr) 100% polyester	310	40	-		157	43	292	59
(R) 100% nylon	587	70	590	70	46	46	416	51
(AA) 70% acrylic 30% wool	684	30	-		725	109	744	106
(PPPF) polypropylene	-		337	50	271	45	450	48

- Data were not taken $\dot{Q}_p$ = peak energy release rate
t_p^* = time interval from start of 150 kW burner to peak energy release rate

Karlsson and Magnusson (1991) offer a relatively simple method following Saito *et al.* (1986) using bench-scale data to predict wall lining flame spread. They have further correlated time to flashover with bench-scale ignitability, flame spread (LIFT), and the cone calorimeter. Figure 12 is a plot of experimental versus predicted time to flashover for several hundred tests. The goal of this work was to produce correlations that used bench-scale test methods to yield full-scale performance. Figure 16 illustrates the predictive capability of the bench-scale test based flame spread calculation procedure.

Mowrer and Williamson (1991) took a similar approach to Cleary and Quintiere (1991) and Saito *et al.* (1986) in an attempt to fit independent data sets on textile wall coverings. Their results show some degree of correlation, but they caution that the bench-scale exposure level and the importance of using "as installed" samples is critical, e.g. adhesive. Their results did verify that for specified values of heat release rate and ignition delay, fires would not propagate. Qualitatively, their results support the work of Cleary and Quintiere (1991).

Several approaches to calculating full-scale burning behavior of interior finishes on the basis of bench-scale flammability properties have been demonstrated to show significant promise. Clearly, more validation is required for the theoretical calculations. All are consistent in the use of calorimeter and LIFT-type property data, all show some degree of correlation, and some indicate that the small-scale test data are inadequate.

4.5 Upholstered Furniture

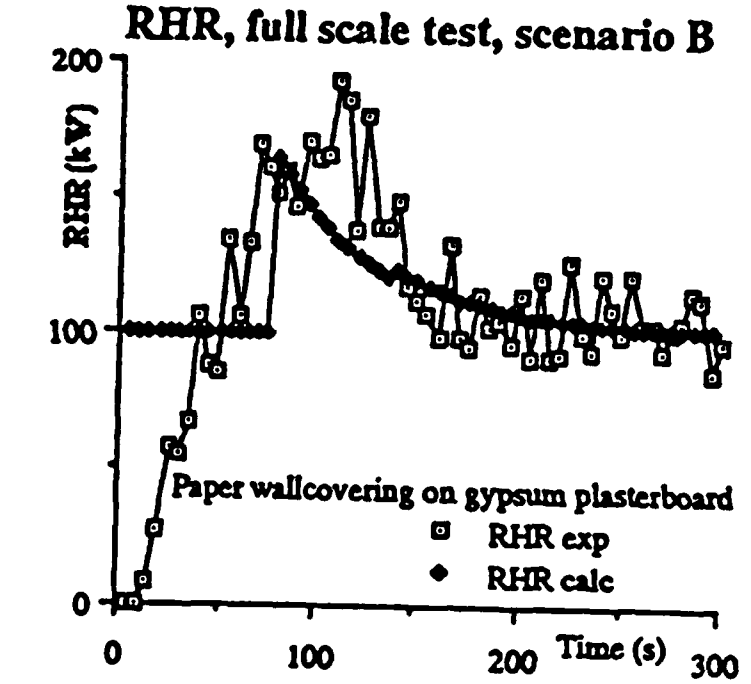
A very successful area of application of using small-scale test data to predict performance is upholstered furniture. An empirical correlation method was developed with incorporated factors to account for physical attributes associated with different furniture styles. Initial work [Babrauskas (1984)] used the following formulation:

$$\dot{q}_{fs} = b \times \dot{q}''_{bs} \times \textit{mass factor} \times \textit{frame factor} \times \textit{style factor} \qquad (31)$$

where q_{fs} = predicted full-scale heat release rate;
b = empirical fitting constant;
q_{bs}"= bench-scale average heat release rate using 25 kW/m^2 irradiance over 180 seconds;
mass factor = total combustible mass;
frame factor = reflects frame material; and
style factor = reflects ectlinear or curved style.

Figure 17 illustrates the agreement between the correlation and full-scale heat release rate.

This was subsequently modified by adding a padding factor and fabric factor while fixing the fitting factor at a set value [Babrauskas and Krasny (1985)]. Additional tests were later run, and the new data were added to the previous work [Babrauskas and Wickström (1989)].



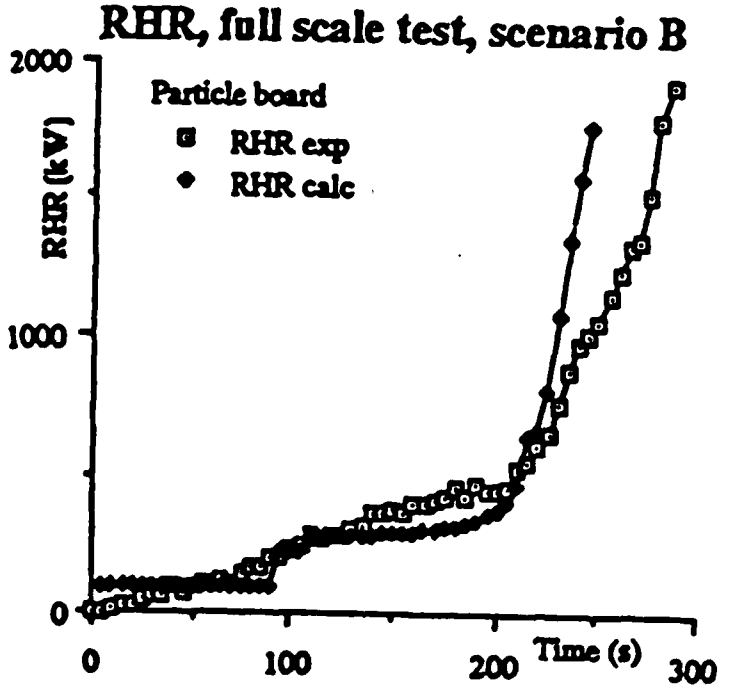


Fig. 16 - Rate of heat release in a full-scale compartment; predicted values vs. experimental data [Karlsson and Magnusson (1991)]

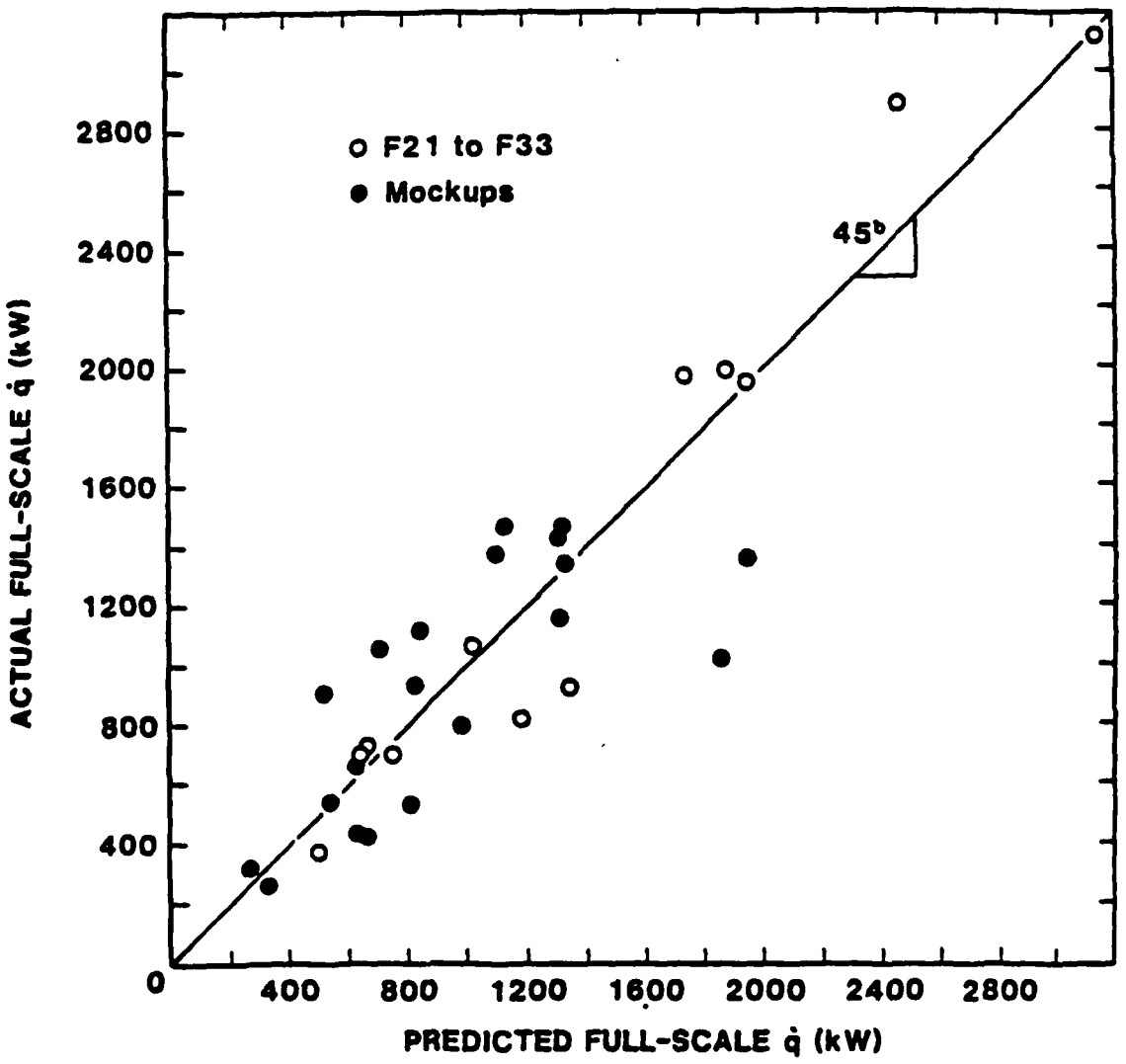


Fig. 17 - Full-scale heat release rates for upholstered furniture; experimental data vs. predicted values [Babrauskas (1984)]

The ability of such a simple correlation, based on a single parameter measured in the cone calorimeter, to predict full-scale behavior over such a wide range of furniture size, type, style, and materials is remarkable.

Other work [Parker *et al.* (1991)] has shown that effects due to different fabrics and foams can be separated out. By plotting full-scale (furniture calorimeter) heat release rates against three-minute averages heat release rates per unit area from the cone calorimeter, it is apparent that the foam components can be distinguished from the fabric contribution as reflected in Fig. 18.

4.6 Scaling Smoke Emissions

There have been a number of papers focusing on the scalability of smoke measurements [Östman and Tsantaridis (1991); Babrauskas (1985); Mulholland, Henzel and Babrauskas (1987)] as well as others addressing smoke scalability through the course of looking at the toxicity problem [Babrauskas *et al.* (1991)]. Two of the sources [Östman and Tsantaridis (1991); Babrauskas *et al.* (1991)] present data for smoke yields per mass burned show the cone calorimeter typically higher than the full-scale by approximately a factor of 2. Östman and Tsantaridis (1991) work with a wide range of wall lining materials show, in Fig. 19, a factor of about 1.33 between the cone calorimeter and room fire tests. These tests included a wide range of wall lining materials such as rigid polymethane foam, textile wall coverings, polystyrene, wood paneling, etc. Two previous works disagree with the factor of two. Mulholland, Henzel, and Babrauskas (1987) find good agreement between bench-scale and real-scale fires with the cone reporting slightly higher yields. Table 12 presents their results. Good results were reported for heptane, crude oil, polyurethane, and wood. Their conclusion was that the specific extinction area, when calculated on a smoke particulate mass basis, was independent of fuel type. Babrauskas (1985) reports a factor of 3.0 difference between full-scale and bench-scale measurements for specific extinction areas based upon per mass of sample pyrolyzed. This factor of 3 is reflected in Fig. 20. There were not enough data presented to cross walk to a comparison of smoke yields.

4.7 Scaling of Fire Evolved Gases [Tewarson and Newman (1986)]

The consensus found in the literature is that the ability to predict full-scale behavior of fire product gases is difficult at best. Babrauskas *et al.* (1988) came to the conclusion that predicting full-scale behavior of products with the cone calorimeter or other small-scale tests is not completely reliable yet. To this end, Östman and Tsantaridis (1991) comment that the "production of smoke and gases is not primarily dependent on materials, but to a higher degree on ventilation conditions and size and shapes of flames." The most difficulties lie with the prediction of CO (carbon monoxide) as "the generation of CO in fires has been shown to be predominantly associated with ventilation and geometry effects in the actual real-scale environment" [Babrauskas *et al.* (1991)]. Yet, even with the difficulties, good results have been obtained and reported [Braun *et al.* (1987)].

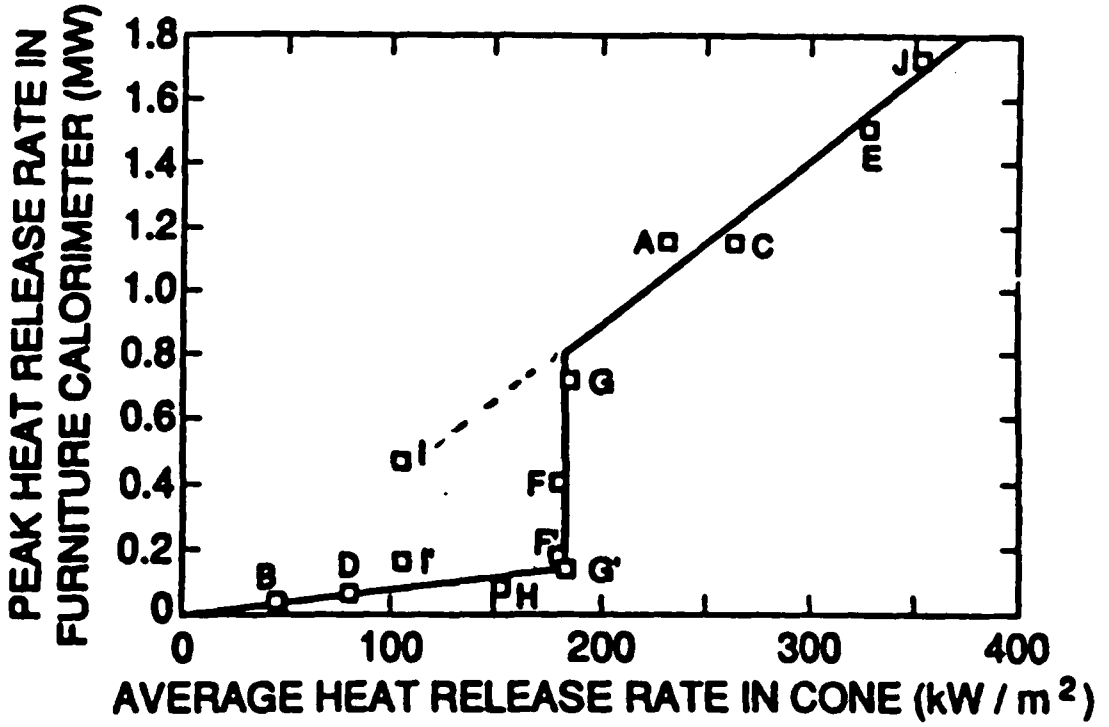


Fig. 18 - Experimental heat release rate data; full-scale peak values vs. bench-scale average values for fabrics and foams [Parker et al (1991)]

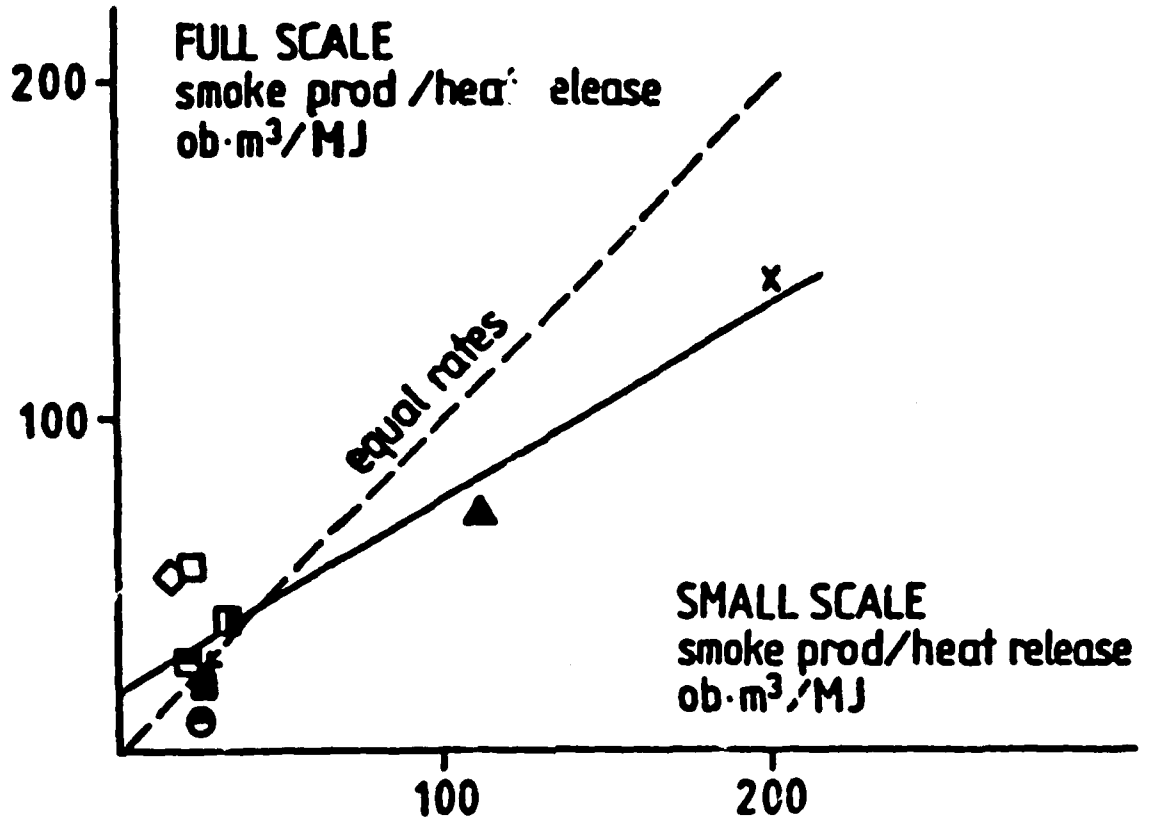


Fig. 19 - Smoke production parameters for wall lining materials full-scale vs. small-scale experimental values (Östman and Tsantaridis (1991))

Table 12. Large and Small-Scale Experimental Smoke Production Data [Mulholland, Henzel, and Babrauskas (1987)]

Fuel/Conditions	Irrad. (kW/m²)	$\dot{Q}$ (kW)	$\dot{m}_s''$ (g/m²-s)	Comb. Eff.	ϵ_1	σ_f (m²/g)	σ_s (m²/g)
Heptane							
Large Scale							
310 mm pool		70	25	0.89	0.009	0.07	7
500 mm pool		240	28	0.94	0.012	0.10	8
Small Scale							
85 mm pool	0	3	10	0.99	0.010	0.06	8
	10	7	24	0.94	0.013	0.08	7
	20	10	35	0.97	0.010	0.07	8
	30	15	58	0.98	0.006	0.05	7
60 mm pool	0	1	9		0.015	0.15	10
	10	3	18		0.016	0.14	9
	20	5	38		0.013	0.12	9
	30	7	59		0.013	0.12	9
Crude oil							
Large Scale							
400 mm pool		65	14	34[a]	0.090	0.96	9.5
600 mm pool		185	(18)		0.085	-	8.7
Small Scale							
85 mm pool	0	1	5	41	0.098	1.06	11.7
	25	2	11	38	0.096	1.01	10.8
	40	4	18	37	0.083	1.00	12.5
	50	5	24	36	0.084	0.98	11.7
Wood							
Large Scale							
sugar pine							
1 crib		56	9[b]	0.66	0.004	0.03	9
3 cribs		254	13	0.69	0.004	0.04	9
Small Scale							
Red oak, 100 mm	25	1	9	0.55	0.002	0.02	11
	50	1	12	0.56	0.004	0.04	11
	75	2	15	0.56	0.006	0.07	13
	100	2	19	0.60	0.011	0.09	10
Polyurethane							
Large Scale							
1 crib		125	12[b]	0.68	0.085	0.74	9.1
2 cribs		310	14	0.68	0.101	0.81	8.5
Small Scale							
100 mm	50	3	5	0.85	0.080	0.89	9.4
PMMA							
Small Scale							
100 mm	25	5	16	0.96	0.015	0.16	11
	50	7	25	0.96	0.014	0.17	13
	75	9	38	0.95	0.012	0.17	11
	100	12	47	0.96	0.016	0.16	11

[a] -- The heat of combustion in MJ/kg.

[b] -- The effective surface area for combustion is taken as half the total surface area of all the individual sticks.

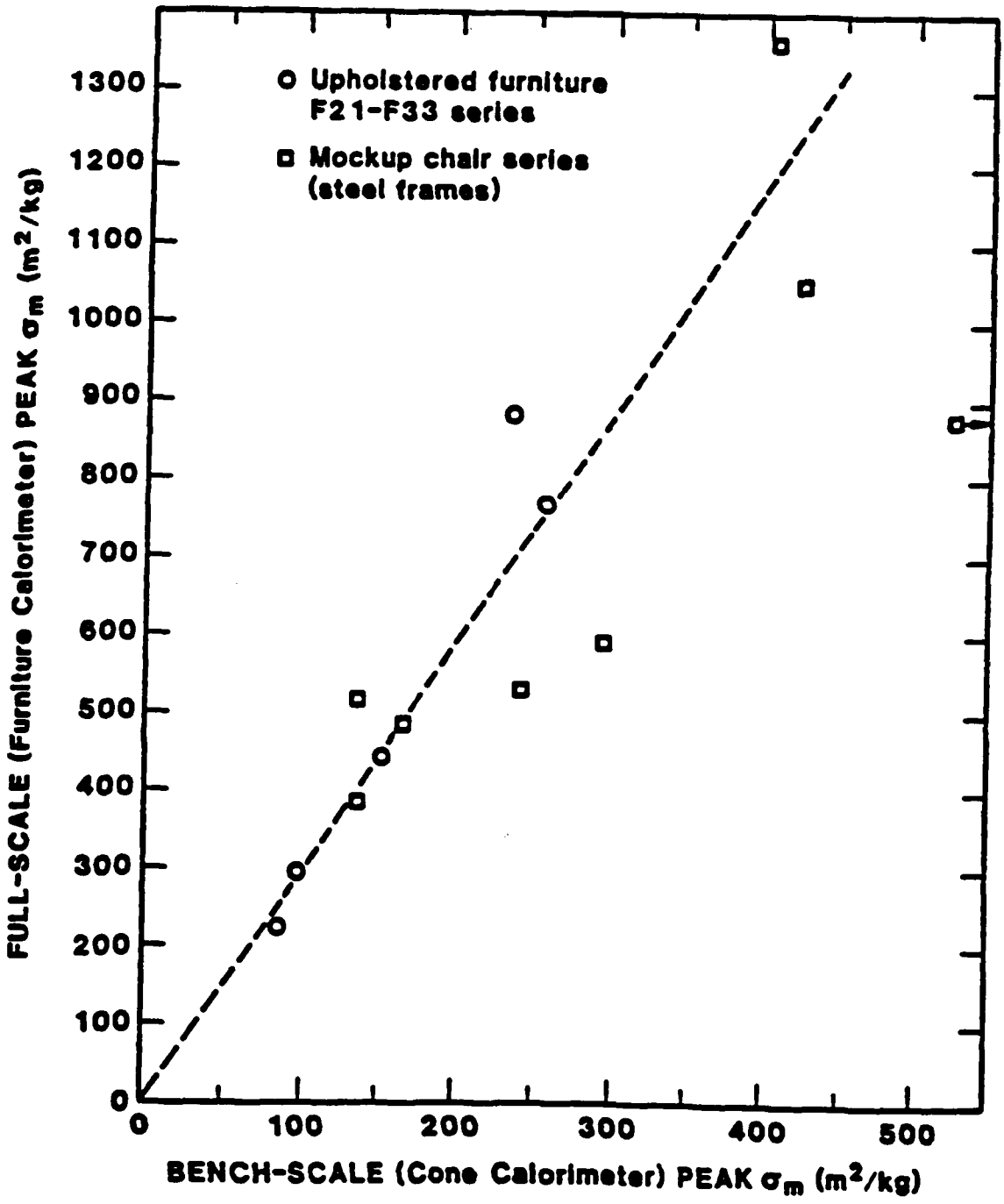


Fig. 20 - Peak values for specific extinction area as experimentally measured: full-scale vs. bench-scale [Babrauskas (1985)]

Braun *et al.* (1987) have shown for both fire retardant and non-fire retardant polymethane foam excellent agreement for both CO and CO_2 yields between the NBS Toxicity test, cone calorimeter, furniture calorimeter, and large-scale tests. Yield ratio comparison data for both fire retardant and room fire retardant polyurethane foams are found in Tables 13 through 16. It has also been noted that for post-flashover fires, the CO yield appears to be material independent with approximately a 0.2 yield rate [Babrauskas *et al.* (1991). Babrauskas *et al.* (1988) report dissimilar findings for CO yields between the cone calorimeter and the furniture calorimeter. They has tested fire retardant and non-fire retardant polystyrene, polyethylene, upholstered chairs, cable array and polyester/glass circuit boards, and the cone CO yields were consistently lower than the furniture calorimeter's CO yields as reflected in Table 13. Although the CO results were not encouraging, the data reported for acid gas yield showed good agreement. HCl, HBr, and HCN were measured in both the cone calorimeter and the furniture calorimeter. These data are also presented in Table 17.

4.8 Cable Insulation

One of the most difficult applications of the prediction of full-scale behavior on the basis of bench-scale test results is in the area of wire and cable insulation. The range of application-dependent variables such as conductor size/weight, cable packaging density, cable size, and geometry, etc. pose a formidable challenge. It is not currently possible to predict the resultant time dependent full-scale fire behavior for a specific wire/cable geometry and bundle.

Several studies on cable fire performance have indicated that the use of bench-scale calorimeter tests are reliable indicators of full-scale fire performance. The work of Tewarson and Khan (1989) at Factory Mutual utilizes a special purpose calorimeter. This calorimeter uses the same principles as the cone calorimeter previously described. The FM calorimeter is used as a basis for categorizing the flammability of wire/cable and has been correlated to full-scale studies. The relevant flammability parameters include heat release rate, time to ignition as a function of applied flux, and critical heat flux for ignition.

These properties are identical to those used to describe the behavior of other combustible materials. Cables are categorized based on a fire propagation index (FPI) which is a function of heat release rate, number of cables and cable diameter, and a thermal response parameter which is a function of ignition time as a function of applied heat flux. Cables are grouped in three categories. This approach has been validated in full-scale.

Fernandez-Pello *et al.* (1991) used a flame spread analysis similar to Quintiere and Cleary (1991) to predict the vertical flame spread characteristics of cables. Their work indicates that the flame spread approach provides a simple and systematic scheme for ranking cable constructions.

There is substantial on-going work in this area using either cone calorimeter/LIFT bench-scale tests or specifically modified but similar bench-scale devices.

Table 13.
[Braun et al. (1987)]

Comparison of CO and CO_2 Yields for Small-Scale Tests, Furniture Calorimeter and Large-Scale Compartment Tests of Non-Fire Retarded Polyurethane Foam 32

	Cotton cover	CO (kg/kg) F[a]	CO (kg/kg) NF[b]	CO_2 (kg/kg) F	CO_2 (kg/kg) NF
NBS Toxicity Test	-	0.02	0.03	1.6	0.2
Cone Calorimeter	-	0.01	0.03	2.3	1.7
Cone Calorimeter	+	0.03		2.0	
Furniture Calorimeter	+	0.04	0.24[c] (0.12)[d]	1.9	9.0[c] (3.6)[d]
Large-Scale Test	+	0.04	0.15[c] (0.09)[d]	2.9	1.0[c] (2.8)[d]

a - Flaming
b - Nonflaming
c - Smoldering
d - After smoldering-to-flaming transition

Table 14.
[Braun et al. (1987)]

Comparison of Yield Ratios of CO_2/CO for the Small-Scale Tests, Furniture Calorimeter and Large-Scale Compartment Tests of Non-Fire Retarded Polyurethane Foam 32

	Cotton cover	Yield ratio of CO_2/CO Flaming	Yield ratio of CO_2/CO Non-flaming
NBS Toxicity Test	-	80	6
Cone Calorimeter	-	200	55
Cone Calorimeter	+	65	
Furniture Calorimeter	+	50	
Furniture Calorimeter	+	30[a]	40[b]
Large-Scale Tests	+	70	
Large-Scale Tests	+	30[a]	7[b]

a After smoldering to flaming transition
b Smoldering

Table 15.
[Braun et al. (1987)]

Comparison of CO and CO_2 Yields for Small-Scale Tests, Furniture Calorimeter, and Large-Scale Compartment Tests of Fire Retarded Polyurethane Foam 32X

	Cotton cover	CO (kg/kg) F	CO (kg/kg) NF	CO_2 (kg/kg) F	CO_2 (kg/kg) NF
NBS Toxicity Test	-	0.05	0.04	1.5	0.3
Cone Calorimeter	-	0.05	0.03	1.9	1.7
Cone Calorimeter	+	0.04		1.7	
Furniture Calorimeter	+	0.05	0.35[a] (0.13)[b]	1.8	8.0[a] (1.9)[b]
Large-Scale Tests	+	0.06	0.17[a] (0.12)[b]	2.2	0.7[a] (2.7)[b]

F = Flaming
NF = Non-flaming
a = Smoldering
b = After smoldering-to-flaming transition

Table 16.
[Braun et al. (1987)]

Comparison of Yield Ratios of CO_2/CO for Small-Scale Tests, Furniture Calorimeter and Large-Scale Compartment Tests of Fire Retarded Polyurethane Foam 32X

	Cotton cover	Flaming	Non-flaming
NBS Toxicity Test	-	30	8
Cone Calorimeter	-	40	60
Cone Calorimeter	+	40	
Furniture Calorimeter	+	40	
Furniture Calorimeter	+	15[a]	20[b]
Large-Scale Tests	+	40	
Large-Scale Tests	+	20[a]	5[b]

a = After smoldering-to-flaming transition
b = Smoldering

Table 17. Gas Yields for Identical Materials from Small-Scale and Full-Scale Experiments [Babrauskas et al (1988)]

Specimen	NFR /FR	CO (kg/kg)			CO_2 (kg/kg)			HCN (kg/kg)			HBr (kg/kg)			HCl (kg/kg)		
		Cone Cal.	Furn. Cal.	Tox. Test.	Cone Cal.	Furn. Cal.	Tox.[d] Test.	Cone Cal.	Furn. Cal.	Tox. Test.	Cone Cal.	Furn. Cal.	Tox. Test.	Cone Cal.	Furn. Cal.	Tox. Test.
TV Cabinet H	NFR	0.015	0.12	0.084	2.28	1.39	2.09	—	—	—	—	—	—	—	—	—
TV Cabinet G	FR	0.109	0.37	0.18	0.67	0.74	0.78	—	—	—	0.069	0.082	0.017	—	—	—
Bus. Machine F	NFR	0.037	0.13	0.17	2.21	1.61	1.98	—	—	—	—	—	—	—	—	—
Bus. Machine A	FR	0.055	0.29	0.30	1.60	1.45	1.53	—	—	—	—	—	—	—	—	—
Chair T	NFR	0.020	0.01	—	1.62	1.89	—	0.002	0.001	—	—	—	—	—	—	—
Chair S	FR	0.051	[a]	—	0.964	[a]	—	0.005	—	—	—	—	—	0.023	—	—
Chair T[b]	NFR	0.016	—	0.025	1.71	—	2.05	0.002	—	0.0007	—	—	—	—	—	—
Chair S[b]	FR	0.055	—	0.15	0.81	—	1.19	0.0023	—	0.0032	—	—	—	0.022	—	—
Cable D	NFR	0.041	0.12	—	1.77	1.61	—	—	—	—	—	—	—	0.112	0.121	—
Cable K	FR	0.060	0.10	—	1.34	1.04	—	—	—	—	—	—	—	0.131	0.133	—
Cable D[c]	NFR	0.029	—	0.050[e]	2.19	—	2.38	—	—	—	—	—	—	ND	—	—
Cable K[c]	FR	0.135	—	0.13	1.00	—	1.26	—	—	—	—	—	—	0.093	—	—
Circuit Bd. C	NFR	0.014	0.10	0.075[e]	2.07	1.71	2.13	—	—	—	—	—	—			
Circuit Bd. L	FR	0.103	0.10	0.15	0.87	1.36	1.24	—	—	—	0.022	—	0.0043			

[a]Could not be determined reliably.
[b]Foam only, no cover fabric.
[c]Wire insulation only.
[d]Determined only from those tests where animals were not used.
[e]Excludes data from the highest mass loading tested, since presumed unrepresentative.
—Not run
ND Not detected

4.9 Summary and Conclusions

1. The ability of modern small-scale test methods to predict full-scale performance has been demonstrated in certain applications.

2. The complexity of the correlation between small-scale tests and full-scale behavior varies from simple algebraic expressions (upholstered furniture) to relatively complicated computer-based calculations (interior finish).

3. The need to test materials in small-scale and large-scale to develop and validate these correlations is obvious.

4. The flammability properties measured in the proposed test methods yield all of the data necessary to characterize fire performance (ignition, flame spread, heat release rate, smoke, and gases).

5. Current test methods can be used to evaluate a wide range of materials and applications and are under active development for non-Naval use. The results of these studies can be directly applied to Navy requirements. The knowledge base is thus leveraged to the advantage of the Navy.

5.0 PROPOSED APPROACH AND NEAR-TERM DEVELOPMENT

This review and analysis has led to a proposed approach for developing criteria and controlling flammability of shipboard materials. The approach is based on the following:

(1) the establishment of performance criteria based on (allowable) full-scale behavior of materials; and

(2) the need to correlate or predict the full-scale performance of materials based on small-scale test methods.

5.1 Performance Objectives

The establishment of performance criteria should continue. The performance objectives should be refined and prioritized. The quantification of these performance objectives should be based on further refinement of a threat analysis, encompassing both peacetime and combat exposure. This should include prioritization of applications based on fire experience data, fuel load surveys, and the availability/interest in improved or replacement materials. These are anticipated tasks under this current project.

5.2 Relating Flammability Properties to Performance Objectives

The second major component of the proposed approach is the most technically challenging. It is structured; however, to minimize the technical risk, the goal is to relate

the allowable hazard indexes (performance objectives) to material burning behavior. The near term effort to attain this goal for selected materials and applications requires the following:

1. select two or three candidate applications (e.g. mattresses, wood crate packaging, interior finish);

2. select two or three materials for each application which reflect the range of (poor, moderate, excellent) fire performance;

3. conduct complete sets of small-scale cone calorimeter and LIFT flame spread measurements.

4. construct a test compartment capable of measuring heat release rate. The test compartment should be approximately 10 x 10 x 10 ft (H) with the ability to easily replace wall materials;

5. use the test compartment to characterize in terms of size, heat flux, and duration a range of ignition sources and exposure fires using actual incidental combustible arrays. Relate these to gas fired exposure fire "simulants;"

6. conduct "full-scale" tests on assemblies of component materials (e.g. a single mattress and a three-tier bunk assembly, a wall/corner interior finish assembly, and/or individual crates and stacked crates with a flue space). Use a range of exposure fire sizes and scenarios;

7. use existing methods and attempt to correlate small-scale results to full-scale "component" results, relative to both full-scale burning behavior and resultant hazard measurements (temperature, visibility, gas concentration) in compartment;

8. evaluate efficacy of approach; and

9. set small-scale test criteria based on performance objectives. Note that in general it will not be possible to set these small-scale criteria without having performed steps 1 through 8 for other applications.

This approach has fairly low technical risk. The worst case scenario is that no correlation is found between the small-scale test methods and full-scale burning behavior. If this occurs, the Navy is still left with full-scale data from which to evaluate the selected materials. These data can still be directly linked with the overall fire protection performance objectives.

An independent decision could then be made relative to the use of cone calorimeter and/or LIFT test methods as a basis for updated passive fire protection

requirements. Since the Navy already owns a cone calorimeter, this is not a major impact.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

1. Bench-scale flammability measurements based on the cone calorimeter and LIFT flame spread test methods have been shown to correlate to full-scale behavior in several applications. Notable among these include the following:
    a. vertical flame spread on interior finish;
    b. time to flash over;
    c. upholstered furniture;
    d. ignition of combustibles; and
    e. cable insulation.

2. The correlation methods for interior finish flame spread have been demonstrated to be valid over a range of interior finish materials. All would require further validation before being used for shipboard materials.

3. Modern bench-scale test methods have been shown to measure the important flammability properties in a way that can be correlated to full-scale performance. These properties include the following:
    a. heat release rate;
    b. minimum flux for flame spread;
    c. thermal inertia;
    d. time to ignition;
    e. mass loss rate;
    f. smoke properties; and
    g. (toxic) gas yields.

4. Full-scale performance objectives based on these calculations are generally limited to conditions where
    (1) significant oxygen starvation has not occurred, and
    (2) pre-flashover temperature conditions exist.

    The degree of priority to these limitations is dependent on the hazard variable of interest (e.g. compartment temperature vs. CO concentration).

5. The bench-scale methods proposed in this report have been proposed elsewhere in both Navy and non-Navy applications for material flammability characterization.

6. The bench-scale test methods proposed in this study are consistent with a wide range of hazard analysis and risk assessment procedures.

7. It is not possible to set small-scale test criteria directly relatable to desired full-scale performance without some full-scale testing to establish correlations and validate any hazard calculations.

8. Any modification of the current passive fire protection requirements should follow the near term development/testing described in Section 5.0 of this report.

6.2 Recommendations

1. Proceed with near term development recommendations detailed in Section 5.0 of this report. The precise materials and applications selected are not crucial. They should include at least one.

2. The Navy should decide which method of establishing performance criteria it wishes to pursue so that the selected approach can be refined during this project. It is, of course, recommended that the approach discussed in Section 2.2 be pursued.

3. A project to evaluate the feasibility of regulating materials on the basis of extreme but low duration thermal insult and low oxygen concentration conditions resulting from unexpended missile fuel be pursued.

4. Proceed with more quantitative threat (exposure) analysis under this task. This would require Naval Safety Center support relative to access to incident summaries.

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Appendix A

Summary of Fire Test Requirements for Naval Shipboard Applications

Material	Specification	Fire Test	Performance Specifications
Acrylic light diffusing panel/windows (lighting fixture windows)	MIL-P-24191	ASTM D 635 ASTM D 2843	Maximum average burning rate -1.35 inches/minute Maximum average burning rate -50
Acoustic absorptic board, fiberglass perforated, fiberglass cloth faced Performance requirements are based upon material attached to, or supplied by, a non-combustible substrate.	MIL-A-23054A(SH)	ASTM E 84	Maximum flame spread index -30 Maximum smoke development -100
Adhesive, flexible unicellular-plastic thermal insulation	MIL-A-24179A	FED-STD-141	Type I: minimum flash point -60°C (140°F) or minimum fire point 75°C (167°F) Type II, Class 1: minimum flash point -3.9°C (25°F) Type II, Class 2: minimum flash point -15.6°C (60°F) Type III: minimum fire point 93.3°C (200°F)
Adhesive, resilient deck covering	MIL-A-21016E		maximum average length of char = 10 inches maximum average sum of combustion and ignition time = 4.0 minutes maximum flame length = 13 inches

Material	Specification	Fire Test	Performance Specifications
Aromatic polyamide upholstery	Commercial	FED-STD-191 Method 5903	maximum char length = 5 inches maximum after flame = 1 second
Block insulation Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-I-2819	ASTM E84	maximum flame spread = 0 maximum smoke developed = 0
Carpet Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	DDD-C-95	FED-STD-372 ASTM E 662	Type II, Classes 1, 2, 3, and 4: minimum incident radiant energy = 0.5 watts/cm^2 minimum D_m (corrected) = 450
Cotton drill mattress cover	CCC-C-426	FED-STD-191 Method 5903	Type I, Class 2: maximum char length = 5.0 inches maximum after flame = 20 seconds
Cotton dock-berth-spring unit mattress cover, treated Use restricted to Officer's berths.	CCC-C-419	FED-STD-191 Method 5903	Type 1, No. 10: maximum char length = 5.0 inches maximum after flame = 20 seconds

Material	Specification	Fire Test	Performance Specifications
Cotton mattress ticking-treated Use restricted to mattresses only.	CCC-C-436D	FED-STD-191 Method 5903	Type II, Class 2: maximum char length = 5.0 inches maximum after flame = 20 seconds
Electrical grade mat or sheet Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-24483	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4 minutes
Epoxy non-skid Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-23003	FED-STD-191 Method 6411	maximum char length = 10 inches maximum combustion time = 4 minutes
Fiberglass cloth, drapery An 8-oz. weight shall be used for materials tested in accordance with Method 5903.	CCC-C-1703	FED-STD-191 Method 5903 ASTM E 662	maximum char length = 1.5 inches maximum after flame = 1.0 second maximum after glow = 2.0 seconds maximum D_m (corrected) = 20
Fibrous glass coating compound for thermal insulation board	MIL-C-19993	ASTM D 93-52 Fire resistance - A	minimum flash point of compounds = -90°F no residual flame or continuous burning after removal of the test flame

Material	Specification	Fire Test	Performance Specifications
Fibrous glass opaque suspended ceiling panel Performance requirements are based upon material attached to, or supported by, a non-combustible substrate.	SS-S-118	ASTM E 84	Type III: maximum flame spread index = 25 maximum smoke developed = 35
Fiberglass insulation, felt	MIL-I-22023D	ASTM E 84 1/4 scale room fire test	Types I and II: maximum flame spread index = 25 maximum smoke developed = 50 minimum flashover time = 10 minutes
End sealer–pipe covering	MIL-C-22395B	ASTM D 92-78 Fire resistance - B	minimum flash point = 300°F maximum burn time of 30 seconds after flame removal
Gasket material, woolfelt, impregnated adhesive, pressure-sensitive	MIL-G-20241 D	FED-STD-191 Method 5903	maximum after flame time = 2.0 seconds

Material	Specification	Fire Test	Performance Specifications
Glass cloth; tape, textile glass, and thread/glass Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-C-0020079G	ASTM D 579 USCG 164.009 FED-STD-191 Method 5903	maximum ignition loss = 3.1% Before treatment: all classes qualify for incombustibility. After treatment: Classes 1, 2, 3, 5, 7, and 9 qualify for incombustibility. Classes 4, 6, 8, and 10 after treatment maximum after flame = 0.0 seconds maximum after glow = 0.0 seconds maximum char length = 0.0 inches maximum flame travel = 1.5 inches
Insulation–blanket Materials tested in accordance with JSCG 164.009 shall pass all requirements for incombustibility.	MIL-I-2818	USCG 164.009	Pass
Insulation–blanket Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-I-23128	USCG 164.009	Pass
Insulation–block Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	HH-I-551	USCG 164.009	Pass

Material	Specification	Fire Test	Performance Specifications
Insulation–board Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-I-742	ASTM E 84 USCG 164.009	Type I: maximum flame spread = 25 maximum smoke developed = 10 Core Only: pass Type II: pass
Insulation–felt Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-I-15475	USCG 164.009	Pass
Insulation–felt Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-I-16411	USCG 164.009	Pass
Insulation–pipe	MIL-I-2781	ASTM E 84	maximum flame spread = 0 maximum smoke developed = 0
Insulation–pipe Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-22344	ASTM E 84	maximum flame spread = 25 maximum smoke developed = 50

Material	Specification	Fire Test	Performance Specifications
Laminate—high pressure Whenever a flame spread higher than 25 is indicated, the material is acceptable since there is no other acceptable material with a lower flame spread.	MIL-P-17171	ASTM E 84	Type I: for table tops maximum flame spread = 75 maximum smoke developed = 50 Type IV: maximum flame spread = 25 maximum smoke developed = 15 Bonded to aluminum: maximum flame spread = 25 maximum smoke developed = 15
Latex—concrete Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-21631	FED-STD-501 Method 6411	maximum char length = 3 inches maximum combustion time = 4.0 minutes
Latex—mastic Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-3134	FED-STD-501 Method 6411	Type II: maximum char length = 10 inches maximum combustion time = 4.0 minutes
Latex—underlay Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-3135	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4.0 minutes
Magnesium aggregate Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-16680 and MIL-D-18873	FED-STD-501 Method 6411	maximum char length = 3 inches maximum combustion time = 4.0 minutes

Material	Specification	Fire Test	Performance Specifications
Plastic sheet–vibrational damping	MIL-P-22581B	ASTM D 635	minimum rating of self-extinguishing
Plastic tiles–vibrational damping	MIL-P-23653C	ASTM D 635	minimum rating of self-extinguishing
Plastic–fire retardant Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-T-18830	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4.0 minutes
Polyaramid An 8-oz. weight shall be used for materials tested in accordance with Method 5903.	MIL-C-24500	FED-STD-191 Method 5903 ASTM E 662	Type I: maximum char length = 5.0 inches maximum after flame = 1.0 seconds maximum after glow = 25.0 seconds maximum D_m (corrected) = 20
Polyaramid/novoloid An 8-oz. weight shall be used for materials tested in accordance with Method 5903.	MIL-C-24500	MIL-C-24500 FED-STD-191 Method 5903 ASTM E 662	Type II: maximum char length = 3.0 inches maximum after flame = 1.0 seconds maximum after glow = 25.0 seconds maximum D_m (corrected) = 20
Polychloroprene–cushioning and mattresses	MIL-R-20092	ASTM E 162 ASTM E 662 Fire retardance	Type II, Class 5: maximum flame spread = 10 (no melting or dripping) maximum D_m (corrected) = 200 Type I: maximum burning time = 30 seconds

Material	Specification	Fire Test	Performance Specifications
Polymeric–interior cosmetic Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-24613	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4.0 minutes
Polyurethane insulation–rigid/foam	MIL-I-24172	ASTM D 1692	Before and after humid aging: non-burning and no flaming droplets
PVF film–aluminum laminate Performance requirements are based upon material bonded to a non-combustible substrate.	L-P-1040	ASTM E 84	Type II, Grad A, Class 1: maximum flame spread = 25 maximum smoke developed = 75
PVF film–aluminum laminate Performance requirements are based upon material bonded to a non-combustible substrate. Performance requirements are based upon material attached to, or suppressed by, a non-combustible substrate.	MIL-L-24518	ASTM E-84	maximum flame spread = 25 maximum smoke developed = 75
PVC–nitrile Materials tested in accordance with USCG 164.009 shall pass all requirements for incombustibility.	MIL-P-15280	ASTM E 84 ASTM E 662	maximum flame spread = 25 maximum D_m (corrected) = 250
Rubber–mattresses and mattress ticks	MIL-M-18351F	FED-STD-191 Method 5903	maximum time of flaming = 6.0 seconds maximum average char length = 2.5 inches

Material	Specification	Fire Test	Performance Specifications
Rubber tile Cement test specimen with MIL-A-21016 must be dry for a minimum of 72 hours. Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	SS-T-312	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4.0 minutes
Spray-on, non-skid Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-24483	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4.0 minutes
Threads, non-skid Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-17951	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4.0 minutes
Terrazzo Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.	MIL-D-3134	FED-STD-501 Method 6411	Type I, Class I, Class 2: maximum char length = 10 inches maximum combustion time = 4.0 minutes
Vinyl–fabric-backed Performance requirements are based upon material bonded to a non-combustible substrate.	CCC-W-408	ASTM E 84	maximum flame spread = 25 maximum smoke developed = 50

Material	Specification	Fire Test	Performance Specifications
Vinyl sheet **Cement test specimen with MIL-A-21016 must be dry for a minimum of 72 hours.** **Specimens tested in accordance with Method 6411 of FED-STD-501 shall have minimum ignition time of 20 seconds.**	L-F-475	FED-STD-501 Method 6411	maximum char length = 10 inches maximum combustion time = 4.0 minutes
Vinyl upholstery	CCC-A-680	FED-STD-191 Method 5903	Class II, Treatment A1: maximum char length = 3 inches maximum after flame = 2 seconds
Vinyl upholstery	CCC-C-700 H	FED-STD-191 Method 5903	Class 4, Treatment A: maximum char length = 3 inches maximum after flame = 2 seconds

MIL-C-24260 Lightweight—Cable, electrical, for shipboard use, general specifications		
Applicable Specification Sheets	**Fire Test**	**Performance Requirements**
MIL-C-24260/1B MIL-C-24260/2B MIL-C-24260/3B MIL-C-24260/4B MIL-C-24260/5B MIL-C-24260/6B	Acid Gas	Jacket - maximum 2 Filler - maximum 2 Insulation - maximum 18
MIL-C-24260/7B MIL-C-24260/8B MIL-C-24260/9B MIL-C-24260/10B	Flame Propagation	No failure
MIL-C-24260/11B MIL-C-24260/12B MIL-C-24260/13B MIL-C-24260/14B MIL-C-24260/15B	Smoke Index NES-711	Jacket - maximum 25 Filler - none Insulation - maximum 10
MIL-C-24260/16B MIL-C-24260/17B MIL-C-24260/18B MIL-C-24260/19A MIL-C-24260/20B MIL-C-24260/22B MIL-C-24260/23B MIL-C-24260/24B	Toxicity Index NES-713	Jacket - maximum 5 Filler - maximum 5 Insulation - maximum 1.5

MIL-C-17G Cables, Radio Frequency, Flexible and Semirigid, General Specifications			
Applicable Specification Sheets		Fire Test	Performance Requirements
MIL-C-17G/2A MIL-C-17G/6B MIL-C-17G/15B MIL-C-17G/16D MIL-C-17G/21C MIL-C-17G/24B MIL-C-17G/28C MIL-C-17G/29C MIL-C-17G/30D MIL-C-17G/31B MIL-C-17G/34B MIL-C-17G/45E MIL-C-17G/47C MIL-C-17G/54B MIL-C-17G/56B MIL-C-17G/64B MIL-C-17G/67C MIL-C-17G/73B MIL-C-17G/74C MIL-C-17G/75F MIL-C-17G/77C MIL-C-17G/78B MIL-C-17G/79D MIL-C-17G/81C MIL-C-17G/81C MIL-C-17G/84B MIL-C-17G/86B	MIL-C-17G/87A MIL-C-17G/90A MIL-C-17G/97C MIL-C-17G/116C MIL-C-17G/119F MIL-C-17G/126B MIL-C-17G/128B MIL-C-17G/129C MIL-C-17G/130D MIL-C-17G/131A MIL-C-17G/132A MIL-C-17G/133C MIL-C-17G/134B MIL-C-17G/135B MIL-C-17G/138A MIL-C-17G/151 MIL-C-17G/152A MIL-C-17G/155A MIL-C-17G/157A MIL-C-17G/160B MIL-C-17G/163A MIL-C-17G/164A MIL-C-17G/165A MIL-C-17G/166B MIL-C-17G/167B MIL-C-17G/176D	No tests required.	None.

MIL-C-17G/52B MIL-C-17G/60C MIL-C-17G/62C MIL-C-17G/65B MIL-C-17G/72C MIL-C-17G/92D MIL-C-17G/93G MIL-C-17G/94F MIL-C-17G/95E MIL-C-17G/110D MIL-C-17G/111C MIL-C-17G/112A	MIL-C-17G/113C MIL-C-17G/127C MIL-C-17G/139C MIL-C-17G/158A MIL-C-17G/159 MIL-C-17G/161 MIL-C-17G/168A MIL-C-17G/169A MIL-C-17G/170A MIL-C-17G/172A MIL-C-17G/174A MIL-C-17G/175B	Flammability	Maximum flame travel rate = 1 inch/minute Maximum cable service after flame = 1 minute No tissue flaming due to specimen drippings.
MIL-C-17G/180B MIL-C-17G/181B MIL-C-17G/182B MIL-C-17G/183B MIL-C-17G/184B MIL-C-17G/185B MIL-C-17G/186B MIL-C-17G/187B MIL-C-17G/188B MIL-C-17G/189B MIL-C-17G/190B	MIL-C-17G/191B MIL-C-17G/192B MIL-C-17G/193B MIL-C-17G/195B MIL-C-17G/196B MIL-C-17G/197B MIL-C-17G/198B MIL-C-17G/200B	Smoke Index NES 711 Toxicity Index NES 713 Acid Gas Generation Flame Propagation	Maximum smoke index = 25 Maximum toxicity index = 5 Maximum acid gas generation = 2.0% Self-extinguishing and small not burn to top of tray

MIL-C-24643 Low Smoke–Cable and Cord, for Shipboard Use, General Specifications		
Applicable Specification Sheets	**Fire Test**	**Performance Requirements**
MIL-C-24643/1B MIL-C-24643/2B MIL-C-24643/3B MIL-C-24643/4B MIL-C-24643/5B MIL-C-24643/6B MIL-C-24643/7B MIL-C-24643/8B MIL-C-24643/12B MIL-C-24643/13B MIL-C-24643/27B MIL-C-24643/28B MIL-C-24643/29B MIL-C-24643/30B MIL-C-24643/31B MIL-C-24643/32B MIL-C-24643/33B MIL-C-24643/34B MIL-C-24643/36B MIL-C-24643/37B MIL-C-24643/38B MIL-C-24643/39B MIL-C-24643/40B MIL-C-24643/43B MIL-C-24643/44B MIL-C-24643/45B MIL-C-24643/46B MIL-C-24643/48B MIL-C-24643/49B MIL-C-24643/50B MIL-C-24643/51B MIL-C-24643/52B MIL-C-24643/53B MIL-C-24643/54B MIL-C-24643/55B MIL-C-24643/56B MIL-C-24643/57B	Acid Gas Flame Propagation Smoke Index NES-711 Toxicity Index NES-713	Jacket - maximum 2 Filler - maximum 2 Insulation - maximum 18 No failure Jacket - maximum 25 Filler - none Insulation - maximum 45 Jacket - maximum 5 Filler - maximum 5 Insulation - maximum 1.5
MIL-C-24643/9B	Acid Gas Flame Propagation Toxicity Index NES-713 Smoke Index NES-711	Equivalent-percent/maximum 18 No failure Maximum 1.5 Maximum 45

MIL-C-24643 Low Smoke–Cable and Cord, for Shipboard Use, General Specifications		
Applicable Specification Sheets	**Fire Test**	**Performance Requirements**
MIL-C-24643/10 MIL-C-24643/41B MIL-C-24643/42 MIL-C-24643/47 MIL-C-24643/58B	Acid Gas	Jacket - maximum 2 Filler - maximum 2 Insulation - maximum 18
	Flame Propagation	No failure
	Smoke Index NES-711	Jacket - maximum 25 Filler - none Insulation - maximum 10
	Toxicity Index NES-713	Jacket - maximum 5 Filler - maximum 5 Insulation - maximum 1.5
MIL-C-24643/11B	Acid Gas	Jacket - maximum 2 Insulation - maximum 18
	Flame Propagation	No failure
	Smoke Index NES-711	Jacket - maximum 25 Insulation - maximum 45
	Toxicity Index NES-713	Jacket - maximum 5 Insulation - maximum 1.5

MIL-C-24643 Low Smoke–Cable and Cord, for Shipboard Use, General Specifications		
Applicable Specification Sheets	**Fire Test**	**Performance Requirements**
MIL-C-24643/14B MIL-C-24643/15B MIL-C-24643/16B MIL-C-24643/17B MIL-C-24643/18B MIL-C-24643/19B MIL-C-24643/20B MIL-C-24643/21B MIL-C-24643/22B MIL-C-24643/23B	Acid Gas Flame Propagation Smoke Index NES-711 Toxicity Index NES-713	Jacket - maximum 2 Filler - maximum 2 Insulation - maximum 18 No failure Jacket - maximum 25 Filler - none Insulation - maximum 35 Jacket - maximum 5 Filler - maximum 5 Insulation - maximum 1.5
MIL-C-24643/24 MIL-C-24643/25B MIL-C-24643/26B	Flame Propagation	No failure

Packaging			
Material	Specification	Fire Test	Performance Requirements
Barrier materials, water-vaporproof, greaseproof, flexible, heat-scalable	MIL-B-1314	ASTM D 568-77	Non-burning or self-extinguishment in maximum of 2.0 seconds.
Cushioning material, polystyrene, expanded, resilient (for packaging uses)	PPC-C-850D	ASTM D 1692	Maximum average time of burning (ATB) of 35 seconds. Maximum average extent of burning (AEB) of 2 inches.
Cushioning material, uncompressed bound fiber for packaging	PPP-C-1120B Grade 1—Flame Resistant Material	ASTM D 3806-79 (Coating sections of test method shall be omitted.)	Maximum experimental flame spread (FS_E) = 30
Foam, combustion retardant, for cushioning supply items aboard Navy ships	MIL-F-87090(SH)	ASTM F 501 ASTM D 2843 ASTM D 2863 ASTM E 162	No dripping Maximum burn length = 1.2 inches Maximum flame time = 0 seconds Maximum smoke generation of 4% Minimum oxygen index of 40% Maximum flame spread index of 1.0
Lumber and plywood, fire-retardant treated	MIL-L-19140E	ASTM E 84 ASTM E 69	Maximum flame spread index of 25 Average final weight loss percentage equal to or less than value for approved specimens. Final weight loss percentage for any individual sample no greater than 5% of qualification value.

Packaging			
Material	Specification	Fire Test	Performance Requirements
Paper, kraft, wrapping	UU-P-268G Type II - Fire Resistant Treated	TAPPI T-461	Maximum flaming time average of specimens 1.0 seconds individual specimen 2.5 seconds Maximum glowing time average of specimens 2.0 seconds individual specimen 2.5 seconds Maximum char length average of specimens 4.5 inches individual specimen 5.5 inches

Appendix B

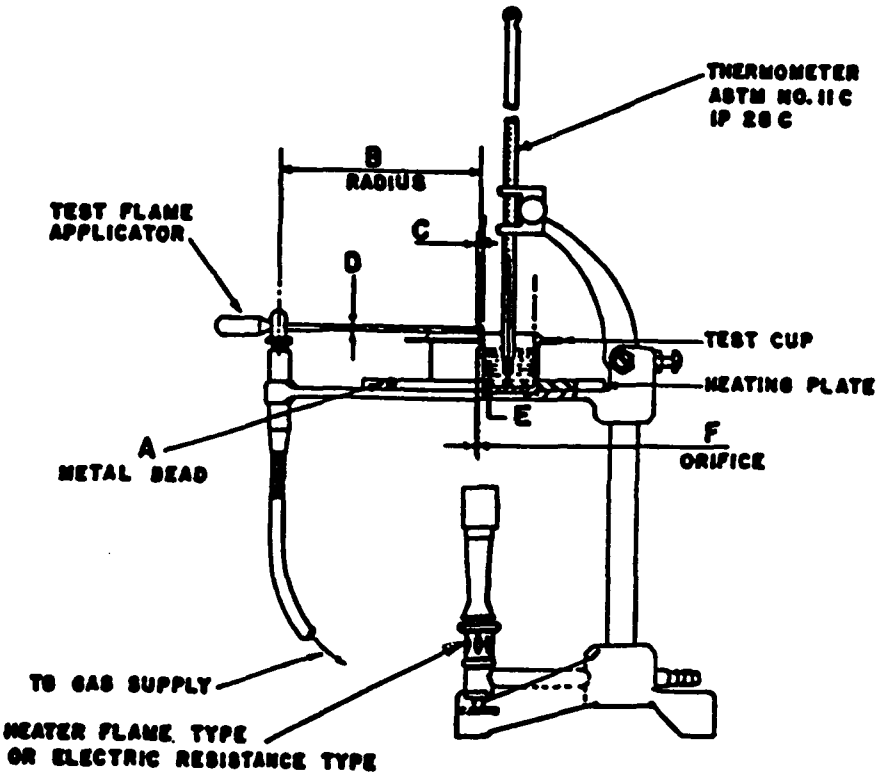
Summary of Flammability Test Methods

ASTM D 92-85

Flash and Fire Points by Cleveland Open Cup

A liquid sample is placed into the test cup. The sample is then heated according to the prescribed procedure. At approximately 50°F below flash point, the small test pilot flame (about 1/8-inch to 3/16-inch in diameter) is passed over the surface of the sample in the cup. The apparatus is schematically presented in Fig. B-1. The sample is continually heated and a flame pass is made every 5°F until the flash point is determined. Testing can continue every 5°F to determine the fire point.

Then results are reported: the flash point of the sample, the lowest temperature of the sample for which the application of the test pilot flame ignites the vapors above the surface of the liquid; and the fire point of the sample, the lowest temperature of the sample where the application of the test pilot flame results in continuous burning of the sample for at least 5.0 seconds.



	Inches		millimetres	
	min	max	min	max
A—Diameter	0.126	0.189	3.2	4.8
B—Radius	6	nominal	152	nominal
C—Diameter	0.063	nominal	1.6	nominal
D		0.078		2
E	0.236	0.276	6	7
F—Diameter	0.031	nominal	0.8	nominal

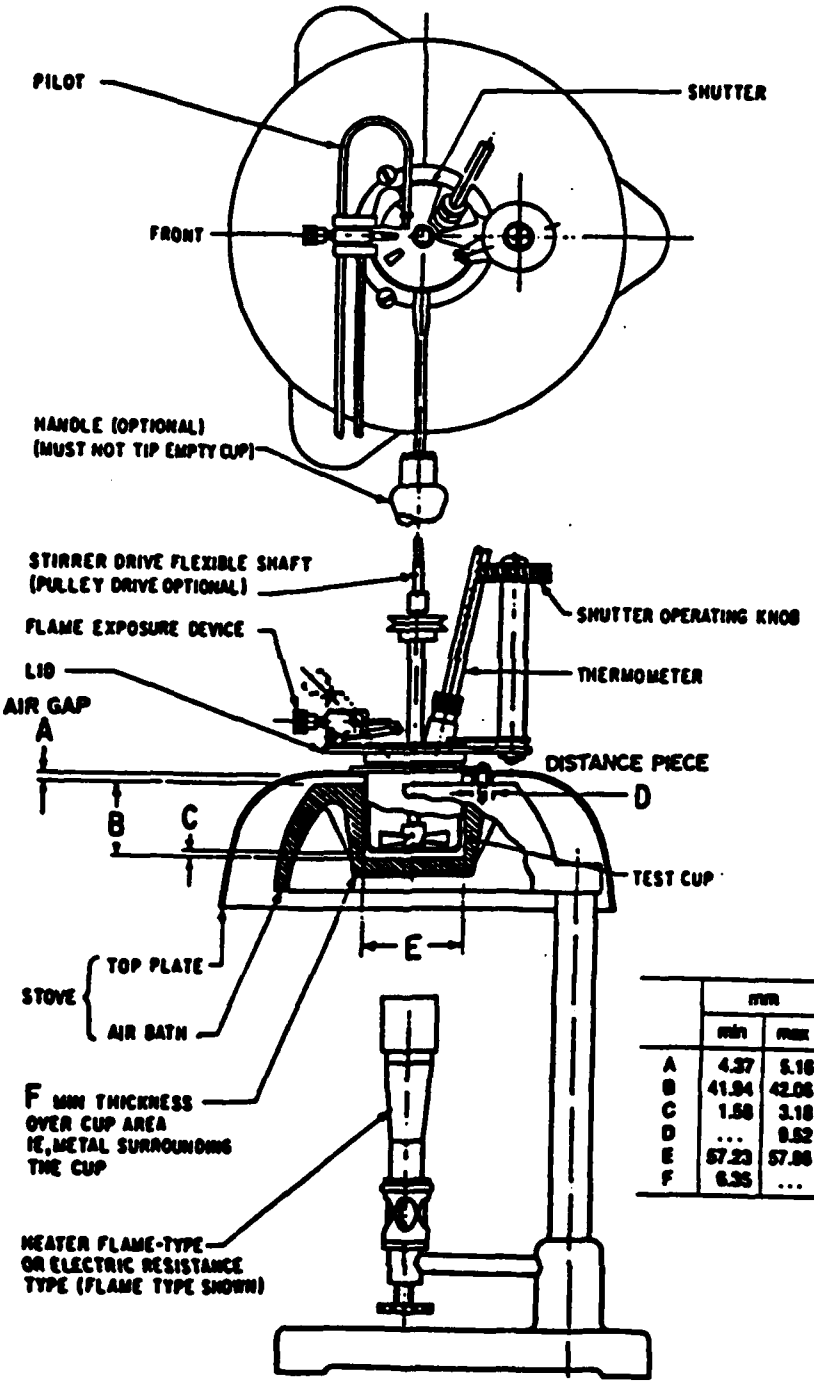
Fig. B-1

ASTM D 93-85

Flash Point by Pensky-Martens Closed Tester

A liquid sample is placed into the test cup. The sample is then heated and stirred simultaneously according to the prescribed procedure. At a temperature in the range of 30-50°F below known flash point, the application of the test flame to the sample should begin. The application of the test flame should then continue occurring every 2°F thereafter until the flash point is determined. The apparatus' dimensions and major components are found in Fig. B-2.

The results reported are the barometric pressure and the flash point of the sample. When the barometric pressure differs from 760 mm Hg (101.3 kPa), the adjusted flash point shall be reported.



	mm		in.	
	min	max	min	max
A	4.37	5.16	0.172	0.203
B	41.94	42.06	1.651	1.656
C	1.58	3.18	0.062	0.125
D	...	9.52	...	0.375
E	57.23	57.86	2.253	2.278
F	6.35	...	0.25	...

Fig. B-2

ASTM D 568-77

Rate of Burning and/or Extent and Time of Burning of Flexible Plastics in a Vertical Position

A plastic sample is fixed in the test apparatus, supported vertically at the top of the specimen. The bottom, free end is subject to a gas flame.

Test specimens, 45 cm long by 25 mm wide by a predetermined thickness, are clamped vertically to the apparatus. A gauge mark is to be made on the 38 cm from the free end. A bunsen burner shall be used to apply a flame tip to the end of the specimen for a maximum of 15 seconds. Once, ignited the flame shall be removed.

Average time of burning (ATB) and average extent of burning (AEB) will be reported if the specimen does not burn to the gauge mark. A burning rate will be reported if the specimen burns to the 38 cm gauge mark.

ASTM D 635

Rate of Burning and/or Extent and Time of Burning of Self-supporting Plastics in a Horizontal Position

A plastic is fixed in the test apparatus supported horizontally at one end. The free end is subjected to a gas flame for 30 seconds.

Test specimens, 125 mm long by 12.5 mm wide by the characteristic thickness, are clamped to the ring stand so that the specimen is horizontal and at a 45° angle width-wise (see Fig. B-3). Two gauge marks, one 25 mm and the other 100 mm from the free end, are made on the specimens. A bunsen burner, producing a 25 mm long blue flame, shall be applied to the end of the specimen for 30 seconds or until the first 25 mm of the specimen is consumed.

Average time of burning (ATB) and average extent of burning (AEB) will be reported in the case where the specimen does not burn to the 100 mm work. In the case where the specimen burns to the 100 mm mark from the ignited end, an average burning rate is reported.

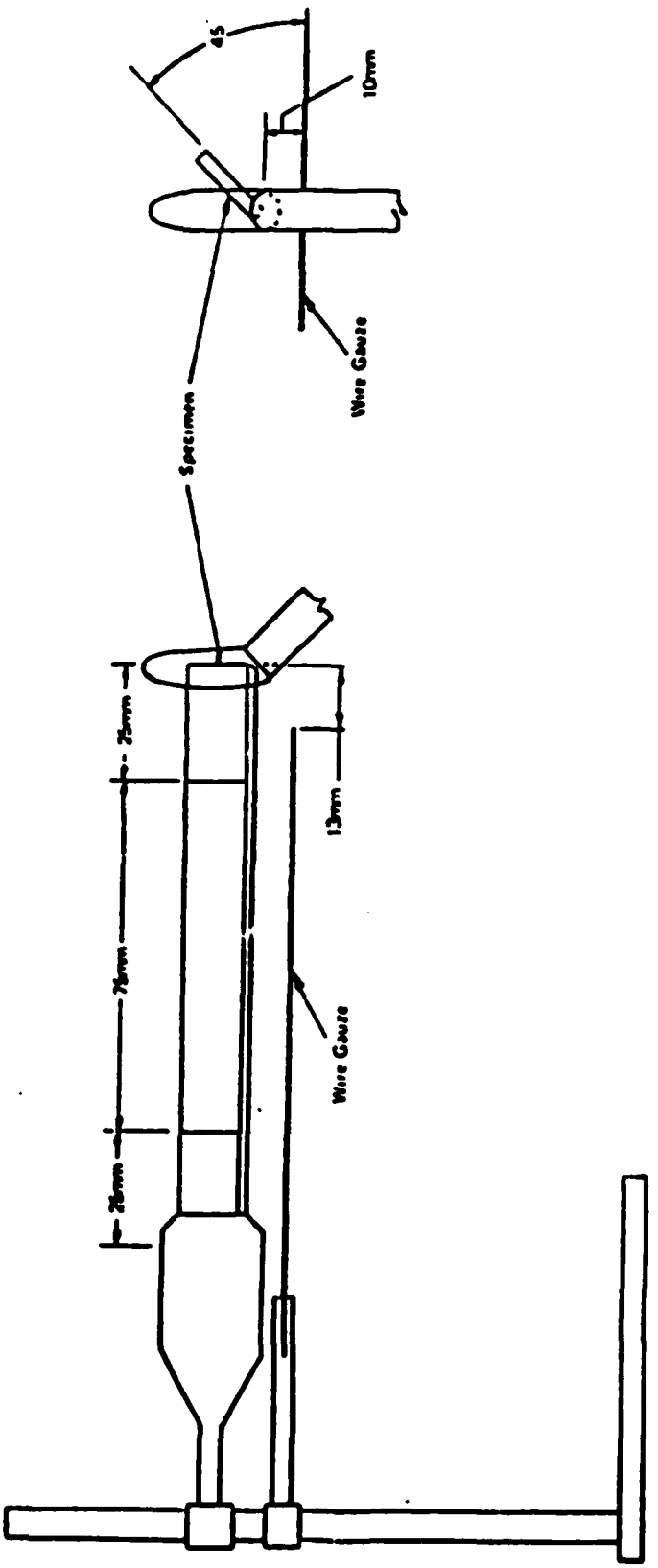


Fig. B-3

ASTM D 2843

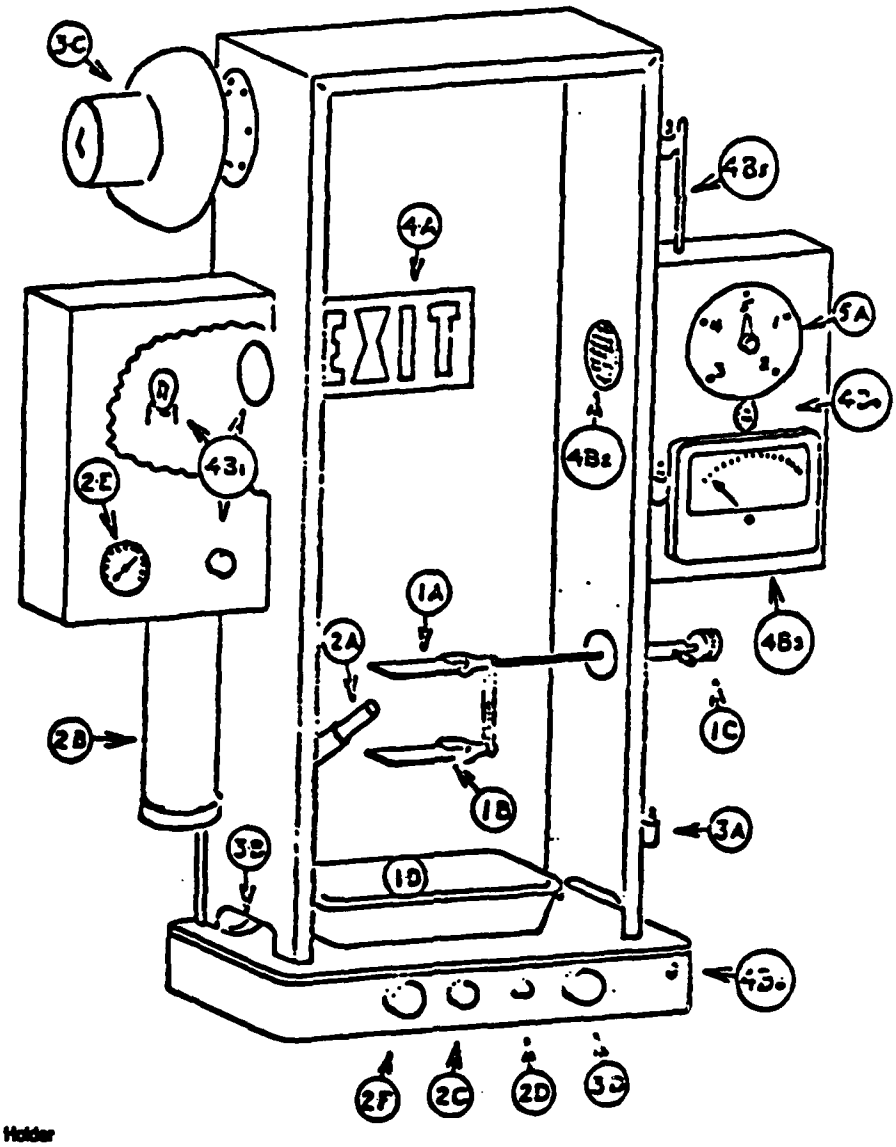
Density of Smoke from the Burning or Decomposition of Plastics

The ASTM D 2843 smoke density test method is used to examine the smoke produced by a burning piece of material. The sample is exposed directly to a premixed propane/air flame which impinges on the corner of the sample. The sample is not subjected to externally applied heat sources.

The sample is square in shape, measuring 25 x 25 mm. The sample is supported in a horizontal position on a wire mesh screen. This allows it to burn completely on all six sides. The sample and holder are inside a test enclosure which measures 300 x 300 x 790 mm high. The enclosure is sealed except for ventilation openings at the bottom. Air enters through these openings as needed for combustion of the sample. The apparatus is pictorally presented in Fig. B-4.

Smoke obscuration is measured and observed by two methods. Light transmittance is measured using a photoelectric system which transverses across a horizontal path at the 480 mm evaluation inside the test chamber. A compact filament microscope lamp is the light source. A photoelectric cell photometer is the receiver. The receiver is temperature compensated. No means is provided to prevent soot buildup on the lenses. Smoke obscuration is also observed by viewing an exit sign on the back wall of the test chamber. The sign measures 90 x 150 mm and is hung at the same height as the photoelectric system.

Values which are measured include time to ignition, time to extinguishment, time for obscuration of the exit sign, and percent light absorbed. Values which are then calculated include smoke produced and smoke density rating.



1. Specimen Holder
   - *A* Stainless steel screen
   - *B* Asbestos sheet
   - *C* Adjusting knob
   - *D* Quench pan
2. Ignition
   - *A* Burner
   - *B* Propane tank
   - *C* Gas shut-off valve
   - *D* Pressure regulator adjustment
   - *E* Pressure indicator
   - *F* Burner-positioning knob
3. Cabinet (shown without door)
   - *A* Hinges (door gasketed three sides)
   - *B* Vents (25-mm (1-in) high opening four sides)
   - *C* Blower (damper on mounting side)
   - *D* Control (blower on when damper is open)
4. Photometer
   - *A* Visual system (exit sign)
   - *B* Measuring system
     - *1* Light source and adjusting transformer
     - *2* Photronic cell and grid (to block stray light)
     - *3* Meter (indicating percent of light absorbed)
     - *4* Temperature compensation
     - *5* Photocell temperature monitor
     - *6* Range change
5. Timer
   - *A* Indicator, 0 to 5 min (friction reset)

Fig. B-4

ASTM D 2863

Measuring the Minimum Oxygen Concentration to Support Candle-like Combustion of Plastics (Oxygen Index)

This test method was developed to study the effects of oxygen concentration on ignition and sustained burning. This test apparatus does not use a radiant heat source to preheat the sample. Instead, the sample is exposed directly to a hydrocarbon diffusion flame 6 to 20 mm long. The flame impinges at the top of the sample to produce candle-like burning. This is a case where the heat and pilot ignition source are the same. The test apparatus is found in Fig. B-5.

The sample is long and thin in shape. The samples' vertical length can vary from 70 to 150 mm. The sample is supported by the bottom end in a glass open top enclosure. The enclosure measures a minimum of 75 mm in diameter and 450 mm in height. Oxygen and nitrogen are premixed and then enter the enclosure at the bottom through a bed of glass beads. The individual gas flow rates are controlled so that the velocity of the gas in the enclosure is a constant 4 cm/s.

Values that are measured include individual gas flow rates, total burning time, and length of downward flame propagation. Testing is repeated until the prescribed criteria are no longer met. The oxygen index is then the minimum oxygen concentration for which the criteria is met.

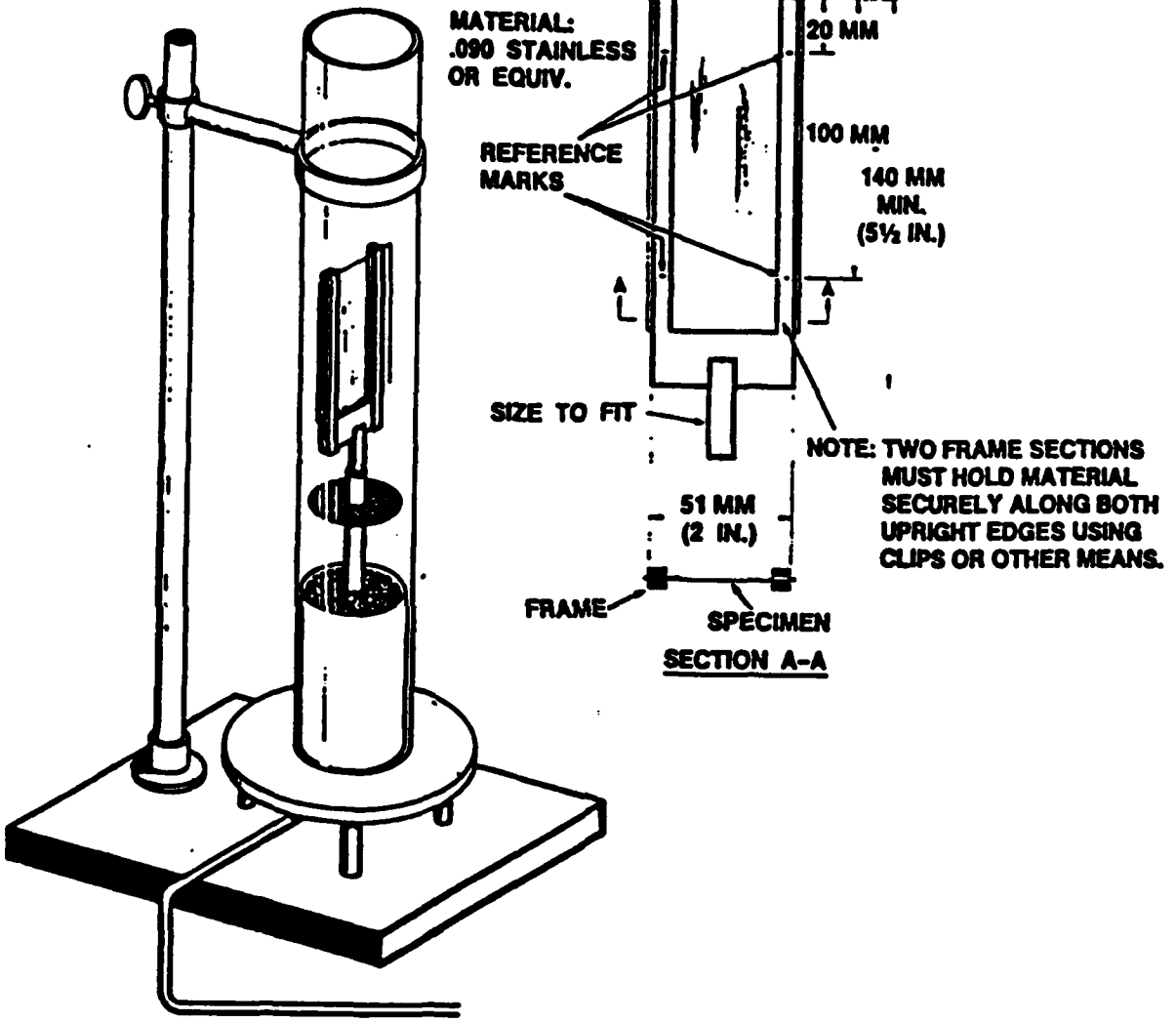

38 MM
(1½ IN.)
6.3 MM (1¼ IN.)
MATERIAL:
.090 STAINLESS
OR EQUIV.
20 MM
100 MM
REFERENCE
MARKS
140 MM
MIN.
(5½ IN.)
A
A
SIZE TO FIT
NOTE: TWO FRAME SECTIONS
MUST HOLD MATERIAL
SECURELY ALONG BOTH
UPRIGHT EDGES USING
CLIPS OR OTHER MEANS.
51 MM
(2 IN.)
FRAME
SPECIMEN
SECTION A-A

Fig. B-5

ASTM D 3806-79

Small Scale Evaluation of Fire-retardant Paints (2-foot Tunnel Method)

A test panel is mounted into the flame tunnel test apparatus at an angle to the horizontal. A gas burner is located at the base of the sample forcing ignition at the bottom of the test panel.

The sample wood test panel, 100 mm wide by 605 mm long by 6 mm thick, is prepared with coating and is placed in the sample holder. This orients the sample at 28° to the horizontal. A detailed diagram of the test apparatus is provided in Fig. B-6. A gas burner located at the base of the sample is used as the exposure source. Flame front progression is recorded every 15 seconds with the gas burner in operation until 60 seconds after the last 15 second readings.

The results recorded is the calculated experimental flame spread rating (FS_E). Other optional measurements include after flaming time, after glow time, panel consumption, degree of intumescence, insulation value, and char dimensions and index.

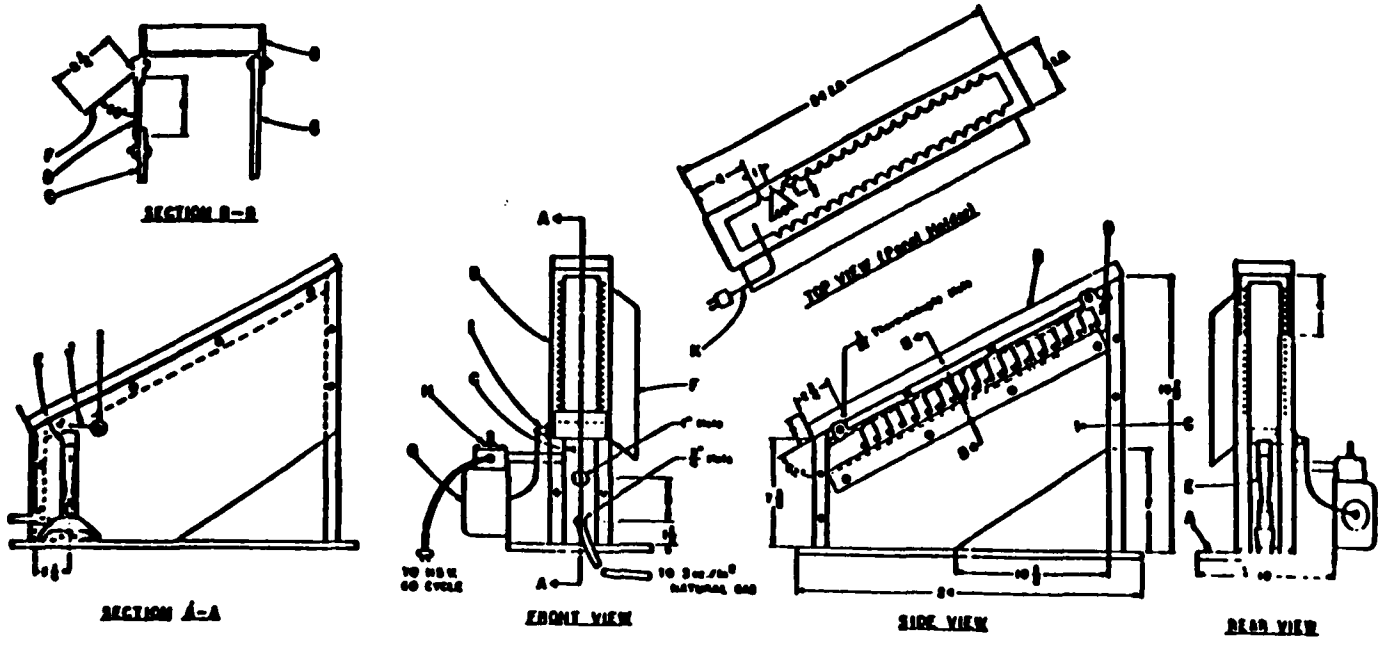


Fig. B-6

ASTM D 3850

This test method was developed to study the way in which the mass loss rate changes as the exposure conditions and, in particular, the ambient air temperature surrounding the sample change. With this apparatus, a small sample is submerged into a hot air flow in a furnace. The furnace is run by a programmable controller which regulates the rate at which the temperature of the air passing through the furnace increases. This rate can be varied but a flow rate of 0.04 to 0.1 L/min is specified by the test standard.

The sample tested must weigh 2 to 20 mg. It is supported in a holder on a scale or load cell assembly. The initial weight is measured, and the percentage lost is calculated from continuous measurements taken during the test. The test is continued until the sample is no longer loosing mass. The temperature of the air immediately above the sample is also continuously measured.

When the sample has reached a zero mass loss condition, it is considered to have completely volatized. At this point, all that is left is char. Therefore, the percent mass remaining can be correlated to the amount of char produced.

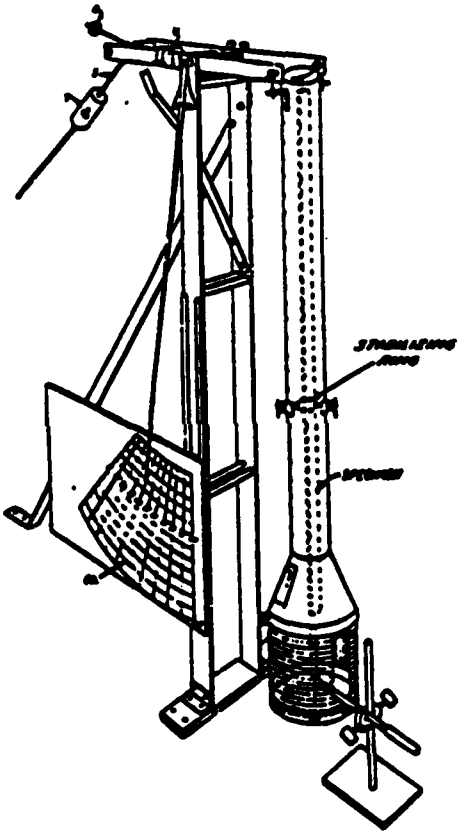
ASTM E 69

Combustible Properties of Treated Wood by the Fire Tube Apparatus

The specimens shall be chosen according to the sampling procedures prescribed. Each sample is then tested in the fire tube apparatus. Two test procedures are given: one for a continuous check on the percentage loss of sample weight, and the other for a final percentage loss sample weight.

A sample, 40 inches long by 3/4-inches wide by 3/8-inches thick, are tested in the apparatus found in Fig. B-7. The sample is exposed to an 11-inch high blue flame from a bunsen burner that produces a temperature of 356 ±9°F at the top of the fire tube. The sample shall be exposed to the flame for 4 minutes after which the flame shall be removed. The test is completed when the flames extinguish or the sample is consumed.

Results reported are percentage moisture content of the samples, final percentage loss of sample weight for each sample, and percentage loss of weight at intermediate times is so desired.



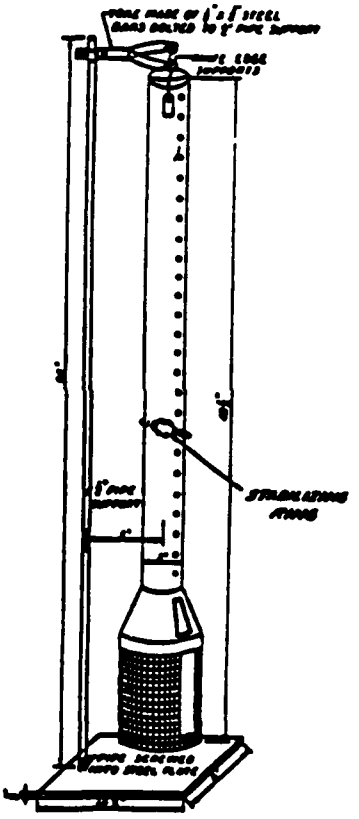


Fig. B-7

ASTM E 84

Surface Burning Characteristics of Building Materials

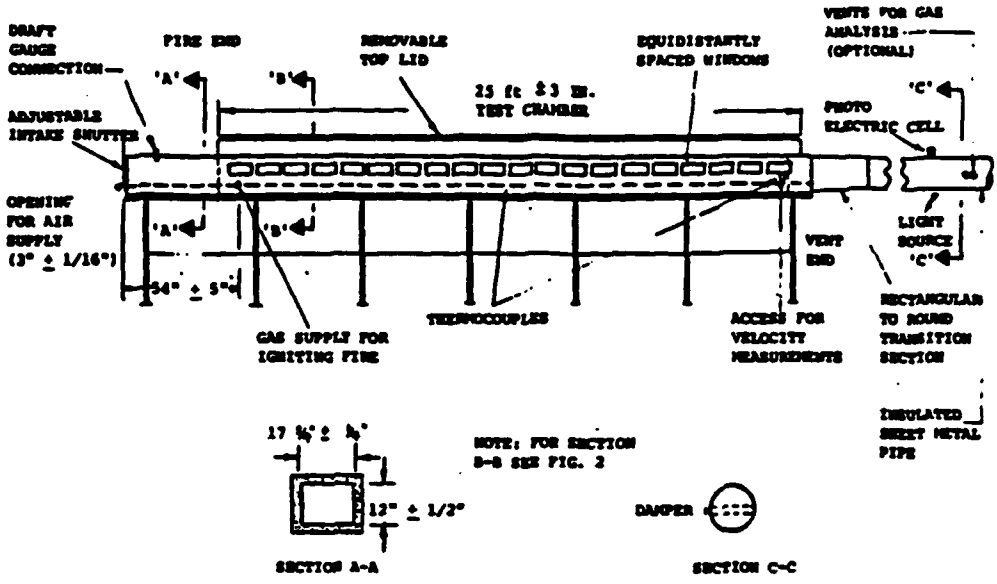
The E 84 tunnel measures the spread of flame in a concurrent air flow. The tunnel does not use a radiant heater to preheat the sample, but instead the air that is flowing through the system is heated by the ignition burners and by the flame as it advances down the length of the sample. This hot air passing over the surface of the sample provides the necessary energy to bring the unburnt material up to its ignition temperature.

The ignition source for the apparatus is two burners located below the sample at the 305 mm position. The burners project a methane diffusion flame upward which impinges on the sample for about 0.9 to 1.2 m down the length of the sample from the one-foot position. The layout of the test chamber and component can be found in Fig. B-8.

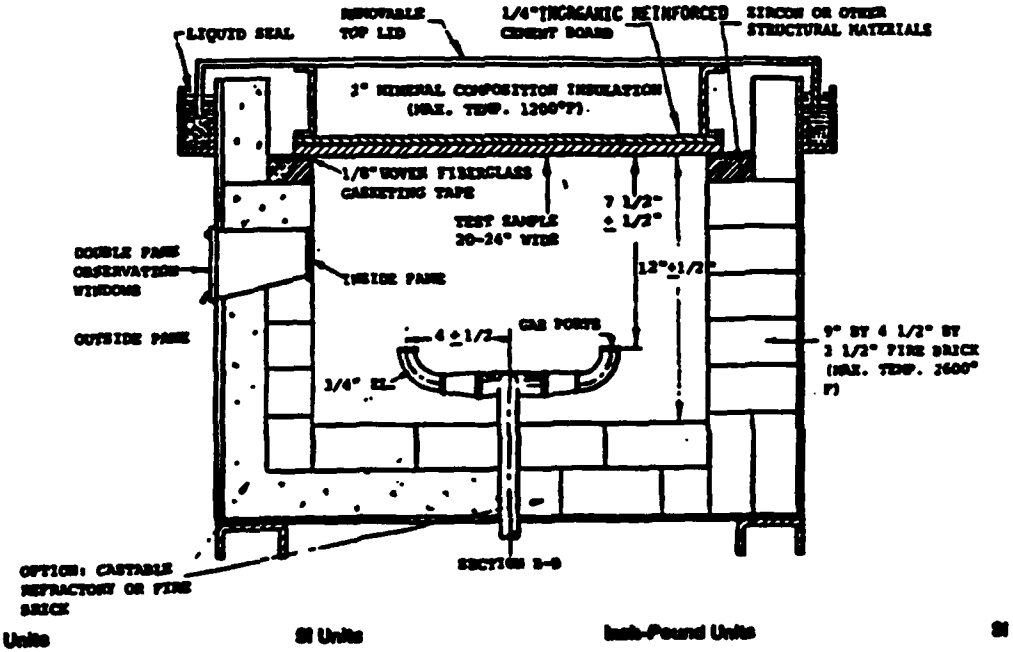
The sample is rectangular in shape measuring 7.3 x 0.51 m. The sample and holder become the roof of the tunnel when in place. The remaining walls are lined with fire brick. Thermocouples are located at the 4.0 m and 7.2 m positions. Fresh air flow is regulated with a damper at the inlet end of the tunnel. The flow rate is controlled so that the velocity in the tunnel is 121 cm/s.

Attached to the exhaust end of the tunnel is a steel exhaust system. Air flow through the exhaust system is a continuation of the flow through the test chamber. Measurements of smoke obscuration are taken in the exhaust stack. Reduction of light transmittance is measured using a photo meter system. The light path is across the stack, perpendicular to the flow of the exhaust gases.

Values which are measured include time for flame to travel a measured distance, exhaust gas temperature, and percent light transmitted. Values that are often calculated include flame spread and smoke development indexes.



Inch-Pound Units	SI Units
12 ± ⅛ in.	305 ± 12.7 mm
17¾ ± ¼ in.	451 ± 6.3 mm
54 ± 5 in.	1371 ± 127 mm
25 ft	7.62 m



Inch-Pound Units	SI Units	Inch-Pound Units	SI Units
⅛ in.	6.3 mm	20 in.	508 mm
2 in.	51 mm	9 by 4½ by 2½ in.	230 by 115 by 65 mm
4 ± ½ in.	102 ± 13 mm	1200°F	649°C
7½ ± ½ in.	191 ± 13 mm	2600°F	1427°C
12 ± ½ in.	305 ± 13 mm		

Fig. B-8

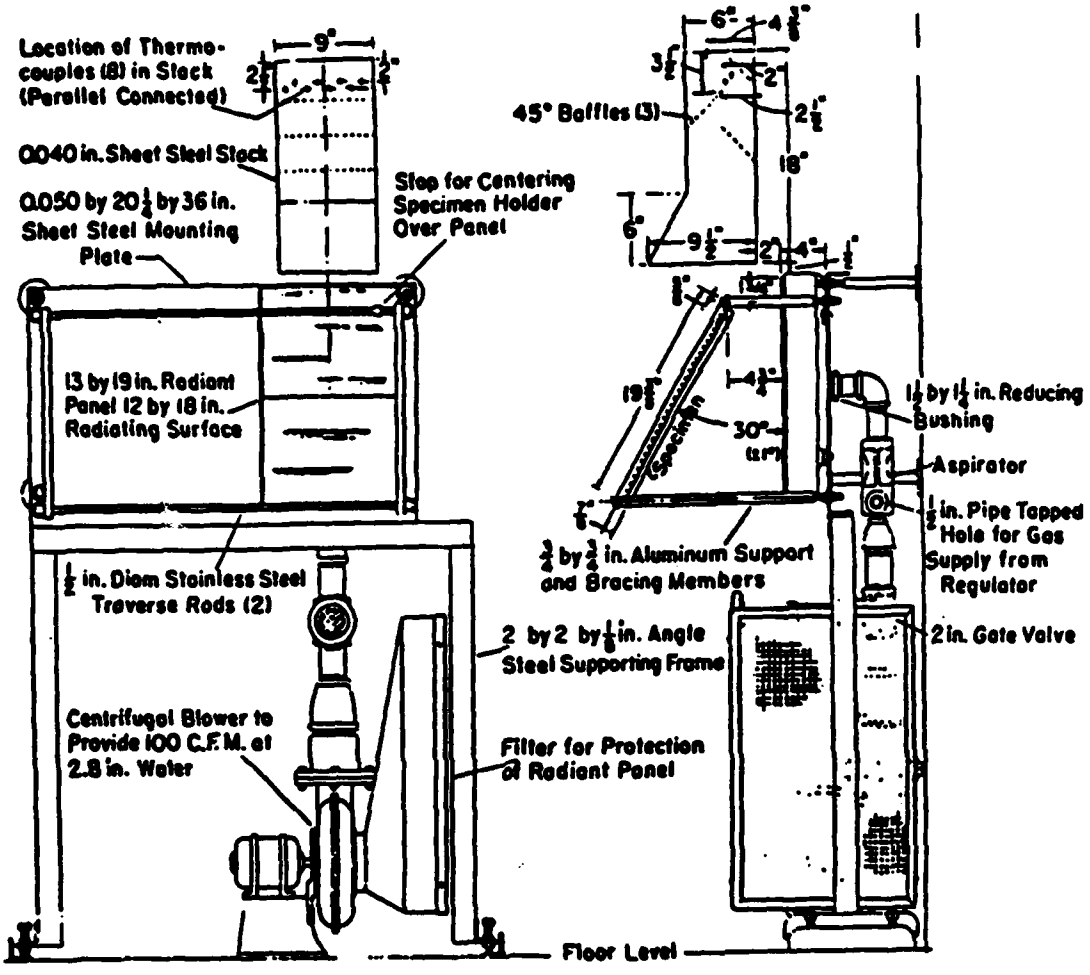
ASTM E 162-83

Surface Flammability of Materials Using a Radiant Heat Energy Source

A sample is fixed in the test apparatus such that it is at an angle to the parallel of the a radiant heat source. This forces ignition at the specimen's upper edge, and if there is flame spread, it progresses downward. The test apparatus' dimensions and components can be found in Fig. B-9.

A specimen of 6 inches wide by 18 inches long and no greater than 1.0 inch thick will be placed in the sample holder. This is located in front of a 12-inch by 18-inch radiant panel using air and gas as the fuel supply. A small pilot flame about 2 inches long is applied to the top center of the specimen at the start of the test. The test commences when the radiant panel is operating at 1238 ±7°F. The test is completed when the flame front has traveled 15 inches or after an exposure time of 15 minutes.

The exposure time and whether the specimen was destroyed will be reported as well as any visual characteristics of the burning, such as running or dripping. An average flame spread index will be reported.



Metric Equivalents

in.	mm	in.	mm
0.040	1.0	6	152
⅛	12.7	9½	241
½	16.0	18	457
⅞	22.2	19½	492
1¾	44	¾ by ¾	19.2 by 19.2
2	51	1¼ by 1¼	38 by 32
2½	64	12 by 18	305 by 457
2.8	71	13 by 19	330 by 483
4	102	2 by 2 by ⅛	51 by 51 by 3.2
4½	111	0.050 by 20¼ by 36	13 by 514 by 914
4¾	121		

100 ft³/min = 47.21 L/s

Fig. B-9

ASTM E 662

Specific Optical Density of Smoke Generated by Solid Materials

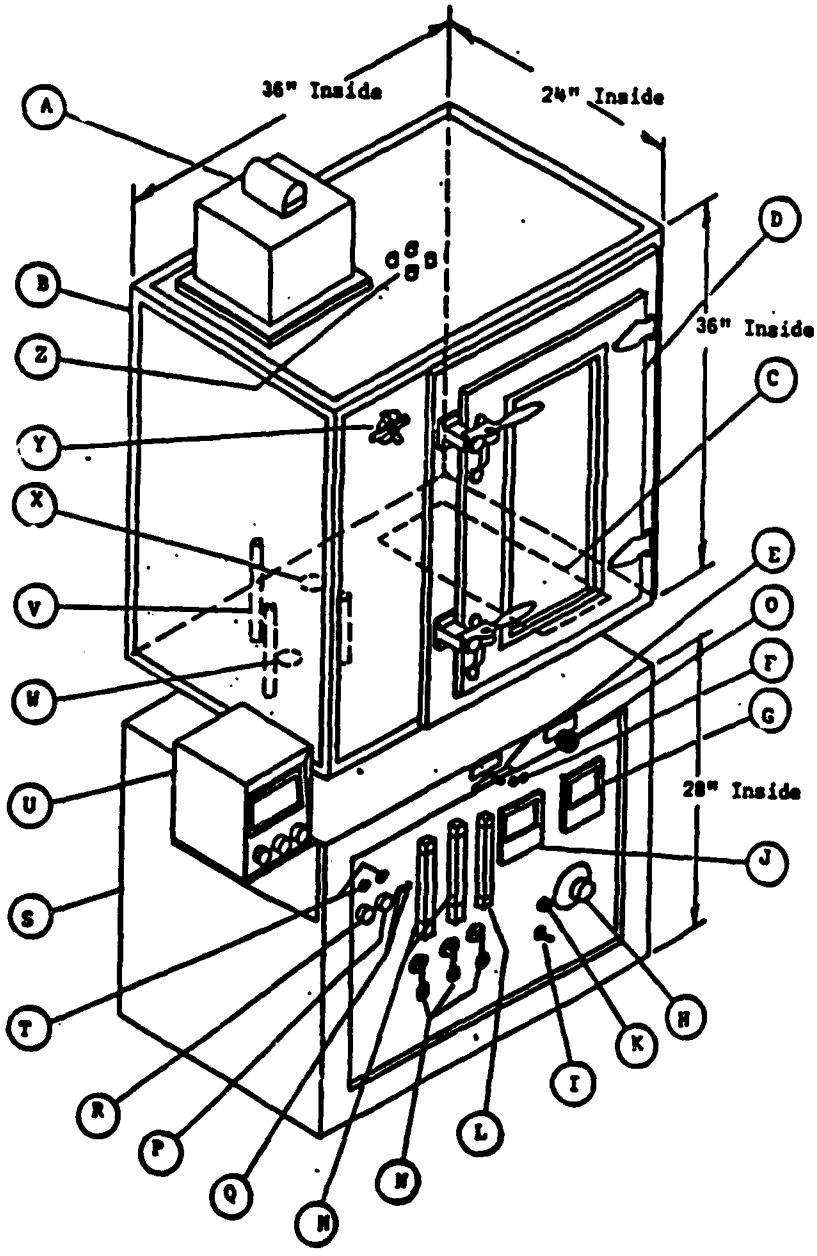
The NBS smoke chamber, identified as ASTM E 662, is used to examine the smoke produced by materials either in the flaming or smoldering modes. The sample is exposed either to a radiant heat source alone, or in conjunction with a pilot flame. The radiant heat is supplied by an electrical radiant heater. The heater is circular, measuring 76 mm in diameter, and is mounted in a vertical orientation parallel to the sample. The heater applies a uniform flux of 25 kW/m^2 to the surface of the sample.

Piloted ignition of the sample is accomplished with a multiple flamelet premixed propane/air burner. The burner is located at the bottom of the sample. It is designed so that some of the flamelets will directly impinge on the surface of the sample and some will be projected up parallel to the surface of the sample. The apparatus can be seen in Fig. B-10.

The sample is square in shape, measuring 76 x 76 mm. The thickness may be varied up to 25 mm. The sample is supported in a vertical orientation. The sample, holder, burner, and heater are located inside a test enclosure which measures 914 x 610 x 914 mm high. The enclosure is sealed except for ventilation openings at the bottom and top. The ventilation openings are only open if the pressure inside the chamber goes negative.

Smoke obscuration is measured using a photometric system which transverses across a vertical path from the bottom to the top of the enclosure. An incandescent lamp is used for the light source. A photomultiplier tube is used as the receiver.

Values which are measured include externally applied flux and light transmitted. Values which are then calculated include specific optical density.



A —Photomultiplier tube housing
B —Chamber
C —Blow-out panel (in floor of chamber)
D —Hinged door with window
E —Exhaust vent control
F —Radiometer output jacks
G —Temperature (wall) indicator
H —Autotransformer
I —Furnace switch
J —Voltmeter (β mode)
K —Fuse holder (furnace)
L —Radiometer air flowmeter
M —Gas and air (burner) flowmeter
N —Flowmeter shutoff valves
O —Sample mover knob
P —Light source switch
Q —Light source voltage jacks
R —Line switch
S —Base cabinet
T —Indicating lamps
U —Microphotometer (photomultiplier)
V —Optical system rods
W —Optical system floor window
X —Exhaust vent damper
Y —Inlet vent damper
Z —Access port

Fig. B-10

ASTM E 1321

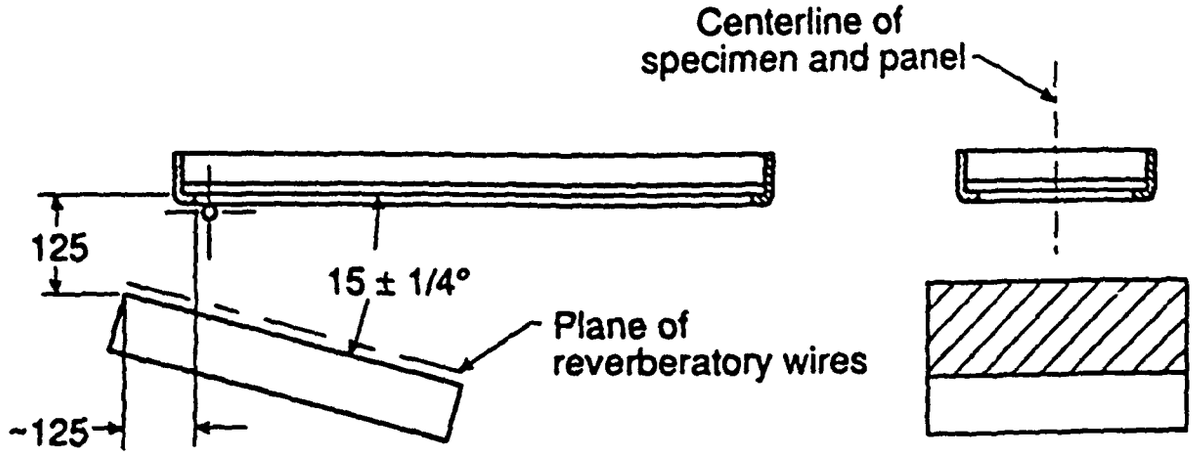
LIFT Method

The LIFT Method combines two separate test procedures: one to determine ignition and the other to determine lateral flame spread.

The sample holder fixes the specimen in a lengthwise vertical orientation. A radiant panel is positioned parallel to the sample at a 75° angle from the perpendicular. The layout is represented in Fig. B-11. The ignition test requires samples, 150 x 150 mm, which are exposed to a nearly uniform heat flux. A series of tests at different flux levels are used to develop an ignition time versus the radiant flux profile. From this profile, the minimum flux for ignition is determined.

The flame spread tests use 150 x 800 mm samples. These samples are exposed to a graduated heat flux which is 10 kW/m^2 higher than the minimum flux calculated above at the hot end. The specimens are preheated for a time which is based upon ignition test results. A horizontal pilot is ignited after the preheat time is over. The flame spread rate on the sample is then recorded.

Data reported includes minimum flux for ignition, surface temperature necessary for ignition, thermal inertion value, the flame heating parameter, and flame front velocities.



NOTE—All dimensions are in millimeters.

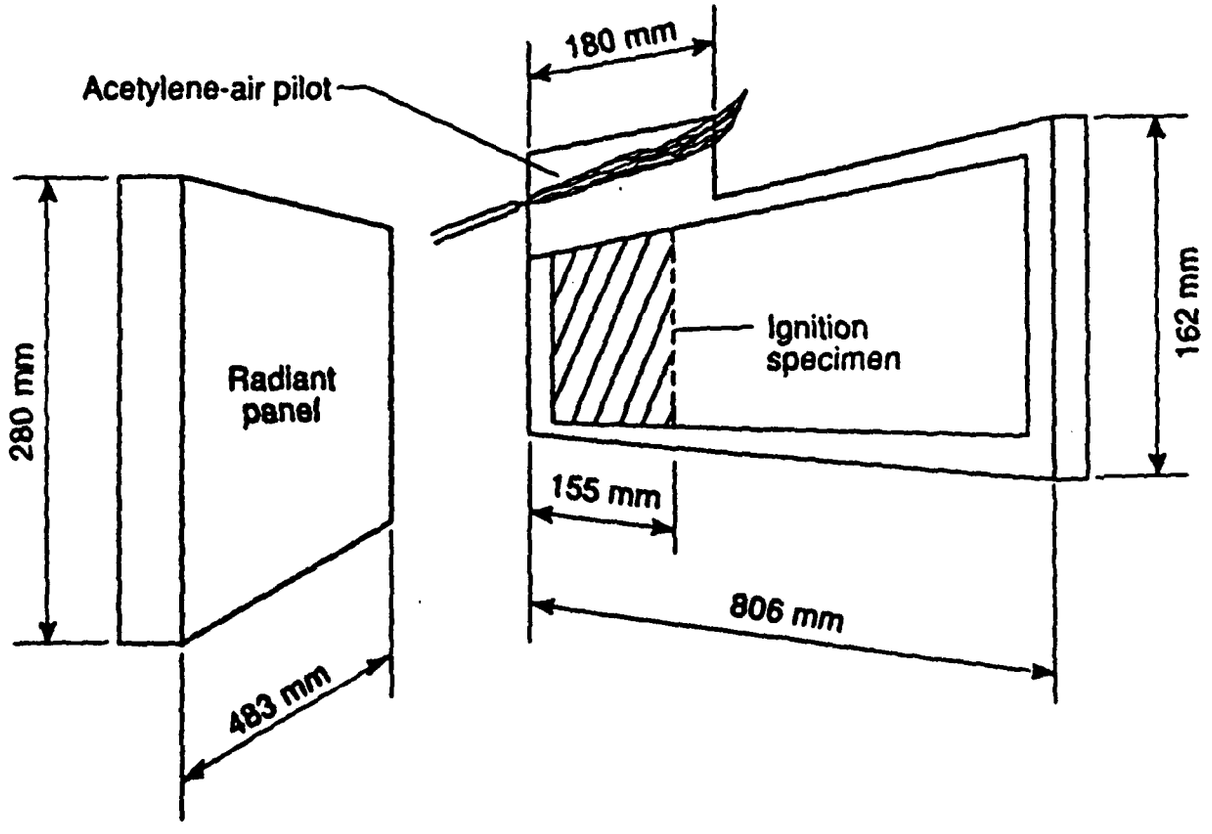


Fig. B-11

ASTM E 1354

Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products using an Oxygen Consumption Calorimeter

The apparatus, the cone calorimeter depicted in Fig. B-12, was initially presented as an improved technique for measuring rate of heat release on bench-scale specimens. Its operation involves an application of the oxygen consumption principle. The oxygen consumption principle states that for most combustibles there is a unique constant, 13.1 MJ/kg O_2, relating the amount of heat released during a combustion reaction and the amount of oxygen consumed from the air. Thus, using this principle, it is only necessary to measure the concentration of oxygen in the combustion system along with the flow rate. The air flow past the specimen is generally set at 24 L/s. This results in a highly fuel-lean combustion condition. In the cone calorimeter, specimens of a material or product to be tested are cut into a 100 x 100 mm size. The thickness depends on the type of product tested and can range from 6 to 50 mm. The specimen edges are protected from burning, and the specimen can be oriented either horizontally or vertically. The specimen is heated by an electric heater in the shape of a truncated cone, hence, the name cone calorimeter. The irradiance to the specimen can be set to any desired value from zero to 110 kW/m^2. If required, external ignition of the specimen is provided by an electric spark. Since a uniform, controlled irradiance is provided, the ignition times themselves, as measured, constitute a suitable test for ignitability. The specimen is mounted on a load cell, and its mass, along with all other instrument data, is recorded to provide mass loss rate data. The smoke measuring system is comprised of a He-Ne laser beam projected across the exhaust duct. The monochromatic light is monitored by a solid-state detector. A second detector serves as a reference to guard against effects of drift and of laser power fluctuations. The optical system is designed to be self-purging and does not use optical windows. To specify the test conditions fully requires specifying the irradiance, the specimen orientation, the use of spark ignition, the test irradiance, and any special specimen preparation techniques.

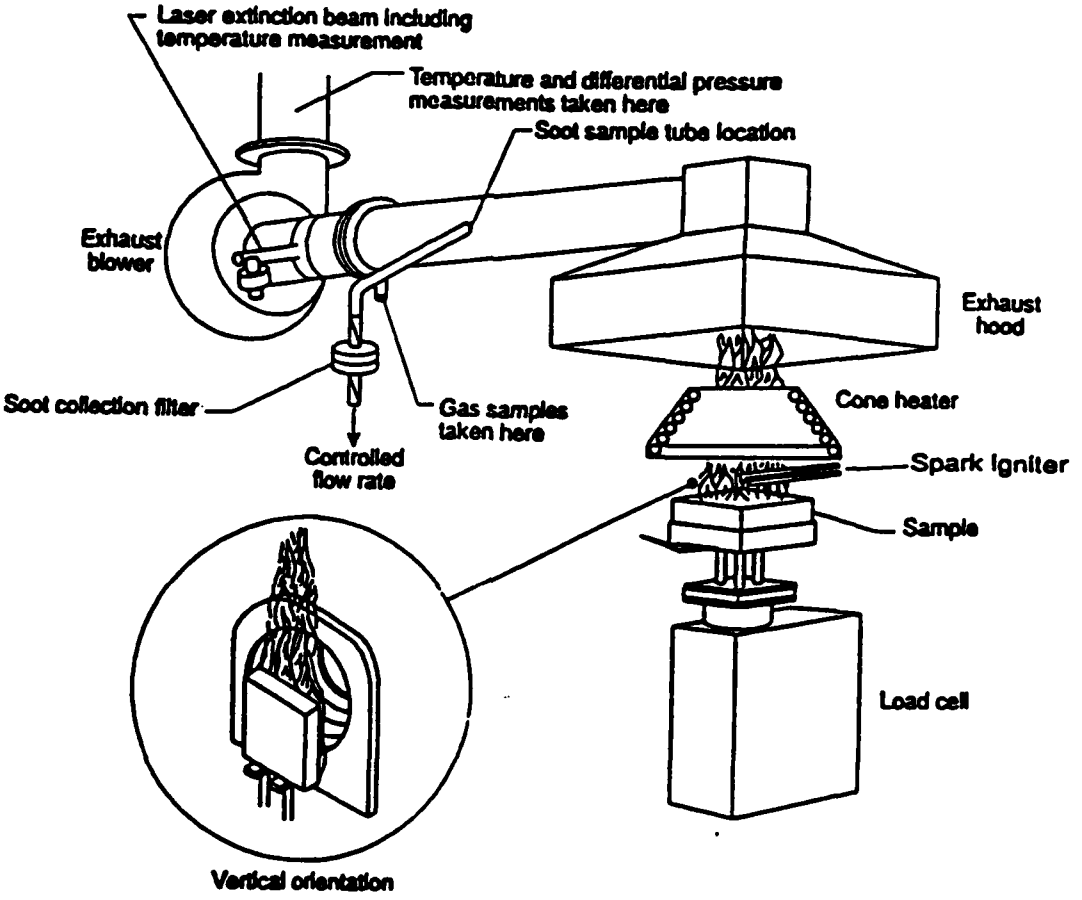

Laser extinction beam including temperature measurement
Temperature and differential pressure measurements taken here
Soot sample tube location
Exhaust blower
Exhaust hood
Soot collection filter
Gas samples taken here
Controlled flow rate
Cone heater
Spark Igniter
Sample
Load cell
Vertical orientation

Fig. B-12

ASTM E 1354 (continued)

The data to be derived from the bench-scale tests in the cone calorimeter constitute a very large set and can be analyzed in a multitude of ways. The data reported include the following:

(a) peak rate of heat release (kW/m^2);

(b) rates of heat release averaged over various time periods, starting with the time of ignition (kW/m^2);

(c) effective heat of combustion (MJ/kg). This will be less than the oxygen-bomb value of the heat of combustion since the combustion is incomplete;

(d) percent specimen mass lost (%);

(e) time to ignition (s);

(f) average smoke obscuration (m^2/kg). Smoke production from a material has the rational units of m^2, representing the extinction cross-section of the smoke. This is normalized by the amount of specimen mass lost (kg); and

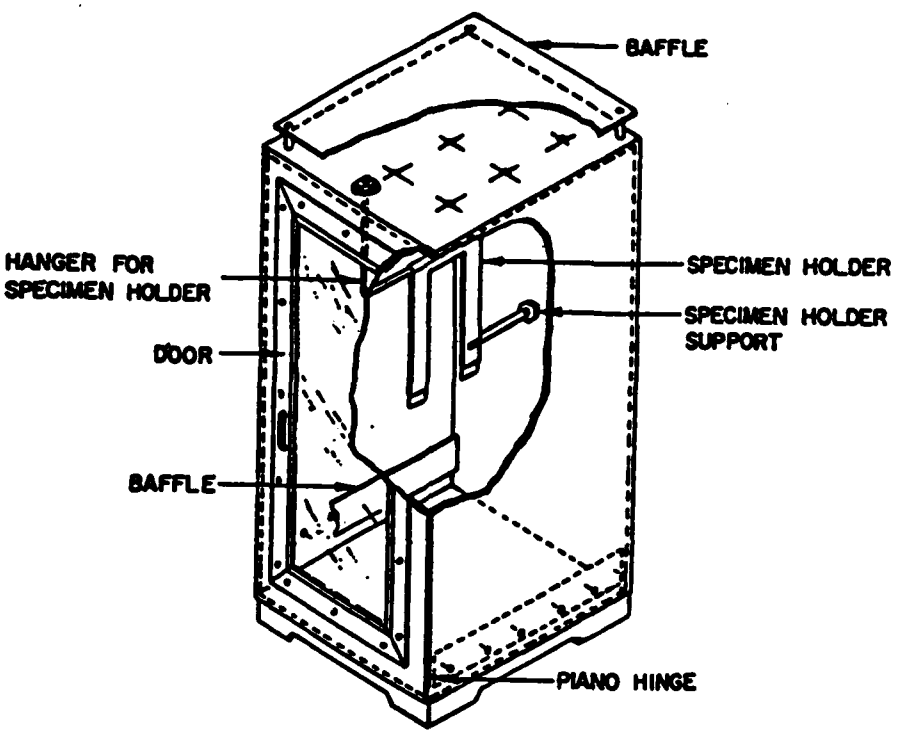
(g) average yields of each of the measured gas species (kg/kg).

ASTM F 501-88

Aerospace Materials Response to Flame with Vertical Test Specimen (for Aerospace Vehicles Standard Conditions)

Test samples measuring 2-3/4 inches by 12 inches are placed in a cabinet equipped as in Fig. B-13. The specimen is supported vertically and lengthwise. In the cabinet will be a gas burner which will be removable. The burner will be positioned such that the top 3/4-inch of a 1-1/2-inch flame will expose the bottom of the sample. As soon as the gas burner is moved so as to expose the sample, the timer is started and the door closed. At the end of the exposure period, the burner is removed and moved at least 3 inches away from the sample.

Results reported include flame time, which is the length of time after the burner is removed that the sample continues to burn; glow time; drip flaming time as well as burn length.


BAFFLE
HANGER FOR SPECIMEN HOLDER
SPECIMEN HOLDER
SPECIMEN HOLDER SUPPORT
DOOR
BAFFLE
PIANO HINGE

F 501

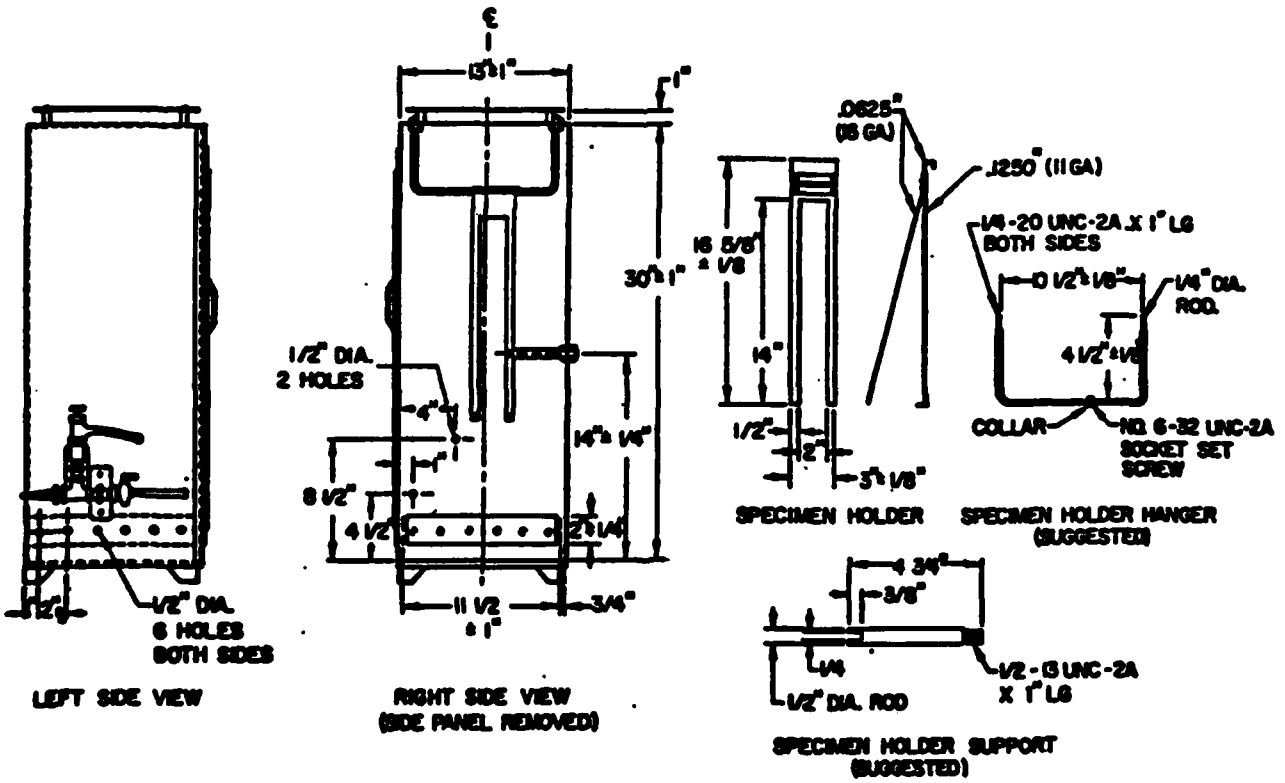

LEFT SIDE VIEW
1/2" DIA. 6 HOLES BOTH SIDES
RIGHT SIDE VIEW (SIDE PANEL REMOVED)
1/2" DIA. 2 HOLES
SPECIMEN HOLDER
.0625" (16 GA)
.1250" (11 GA)
SPECIMEN HOLDER HANGER (SUGGESTED)
1/4-20 UNC-2A X 1" LG BOTH SIDES
1/4" DIA. ROD
COLLAR
NO. 6-32 UNC-2A SOCKET SET SCREW
SPECIMEN HOLDER SUPPORT (SUGGESTED)
1/2" DIA. ROD
1/2-13 UNC-2A X 1" LG

Fig. B-13

Fire Resistance - A

MIL-C-19993A

Strips of fibrous glass tape, 6 inches long by 1-1/2 inches wide by 0.007 inches thick are coated with a thin layer of the compound to be tested. These strips are then dried in a heated oven at 228°F for 20 hours. A Meker burner is used to subject the bottom 1/2-inch of the sample directly to the flame. The specimen is vertically suspended from a clamp. After 5 seconds of exposure time to the flame, the burner is removed.

Reported information includes the observations as to residual flame and continuous burning.

Fire Resistance - B

MIL-C-22395B

Strips of fibrous glass tape, 6 inches long by 1-1/2 inches wide by 0.007 inches thick are coated with a thin layer of the compound to be tested. The test strips are allowed to air dry for 72 hours. The strips are then dried in a heated oven at 228°F for 20 hours. A Meker burner is used to subject the bottom 1/2-inch of the sample directly to the flame. The specimen is vertically suspended from a clamp. After 5 seconds of exposure time to the flame, the burner is removed.

Reported information includes the observations as to residual flame and continuous burning.

Fire Retardance

MIL-R-20092K

The specimens can be of any convenient length with a 1/4-inch by 1/2-inch cross section. The sample is held horizontally. A candle flame is applied to the end of the sample for 1 minute. The flame is then removed, and the time that the specimen continues to burn after the removal of the flame is recorded as the flame propagation time.

Acid Gas Generation

MIL-C-17G, MIL-C-24640, MIL-C-24643

A weighed sample, 0.25 to 0.5 g, is placed in a silica boat which is placed in a silica tube. An air supply which provides flow through the furnace and collection system will support 1 liter per minute. After the air passes through the furnace, it then passes through four absorber flasks containing deionized water. The furnace is heated to 800 ±10°C over the first 40 minutes. The temperature is held there for 20 minutes. The contents from the absorbtion flasks are then analyzed to determine the total acid equivalent relative to hydrochloric acid. See Fig. B-14 for the test apparatus.

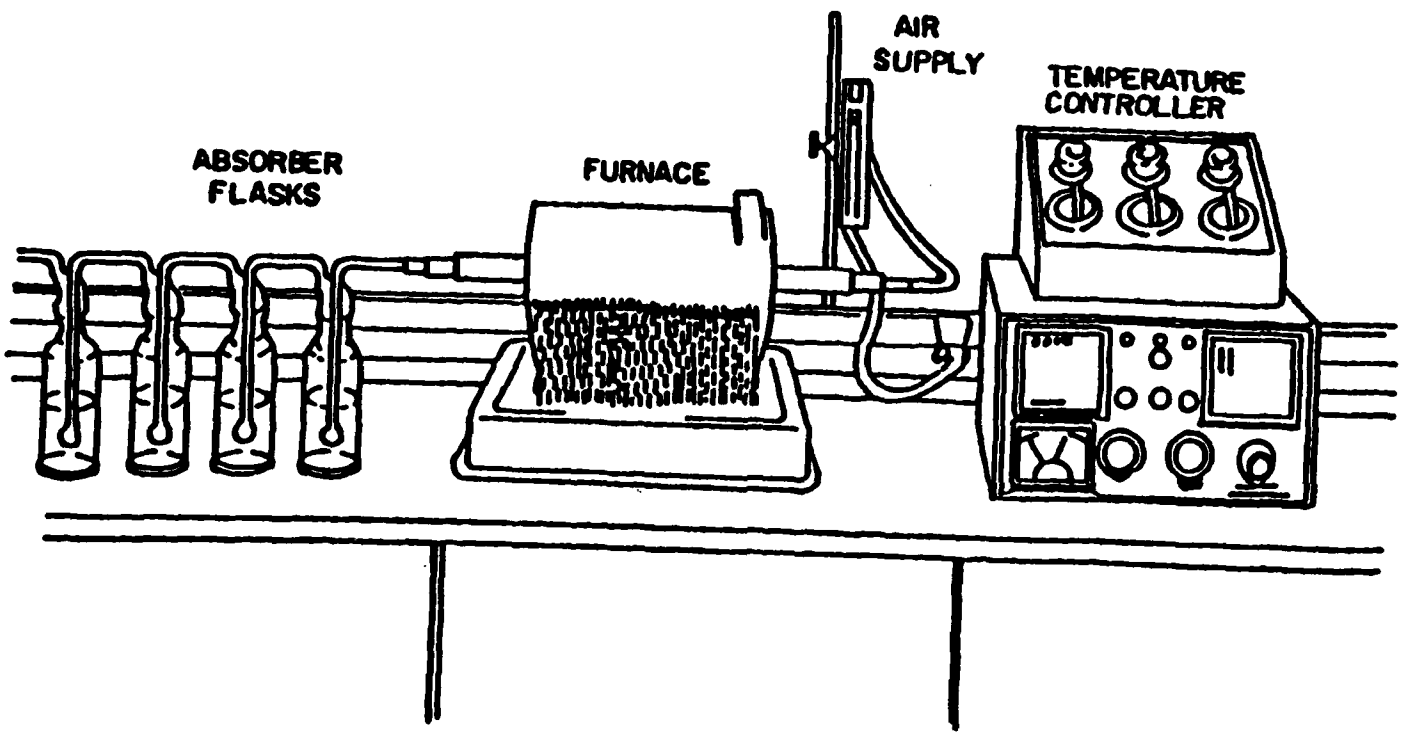

AIR
SUPPLY
TEMPERATURE
CONTROLLER
ABSORBER
FLASKS
FURNACE

Fig. B-14

Flammability

MIL-C-17G

The specimen is to be approximately 24 inches in length. The apparatus is to be a 1 ft^3 test chamber. The lower end of the sample is held by a clamp and the other end passes over a pully at the top of the chamber. This allows a weight to be placed on the free end, thus holding the cable sample taught and at a 60° angle to the horizontal as well as in a plane parallel to the back of the chamber. Both the top and front of the chamber are open.

A gas burner having a 3-inch flame with a minimum of a 1-inch runer cone which has a minimum flame temperature of 954°C is to be used. The burner is used to apply the flame to the cable for 30 seconds at a point which allows 9-1/2-inches of vertical distance between the point of application and a facial tissue suspended below.

Results reported include the distance of flame travel, the time of burning after flame removal, the presence or absence of flames in the tissue as well as physical failure of the cable.

Federal Test Method Standard No. 372

Test for Critical Radiant Flux of Carpet Flooring Systems

This method measures the critical radiant flux of carpet samples exposed to a flaming ignition source in a graded radiant heat exposure environment. The quantity measured is the critical radiant flux at flame-out.

The sample holder fixes the specimen in a horizontal orientation. A radiant panel is positioned above the sample at a 30° angle from the horizontal. The apparatus can be seen in Fig. B-15. A sample, 20 cm by 100 cm, is clamped as described with padding over a piece of asbestos/cement board. The radiant panel is preheated, and then the specimen is placed into apparatus after the pilot flame has been lit. After a two-minute pre-heat, the pilot flame is applied to the sample for ten minutes. The point at which the flame front stops at indicates the critical radiant flux at flame out.

Data reported includes burning characteristics and average critical radiant flux with standard deviation.

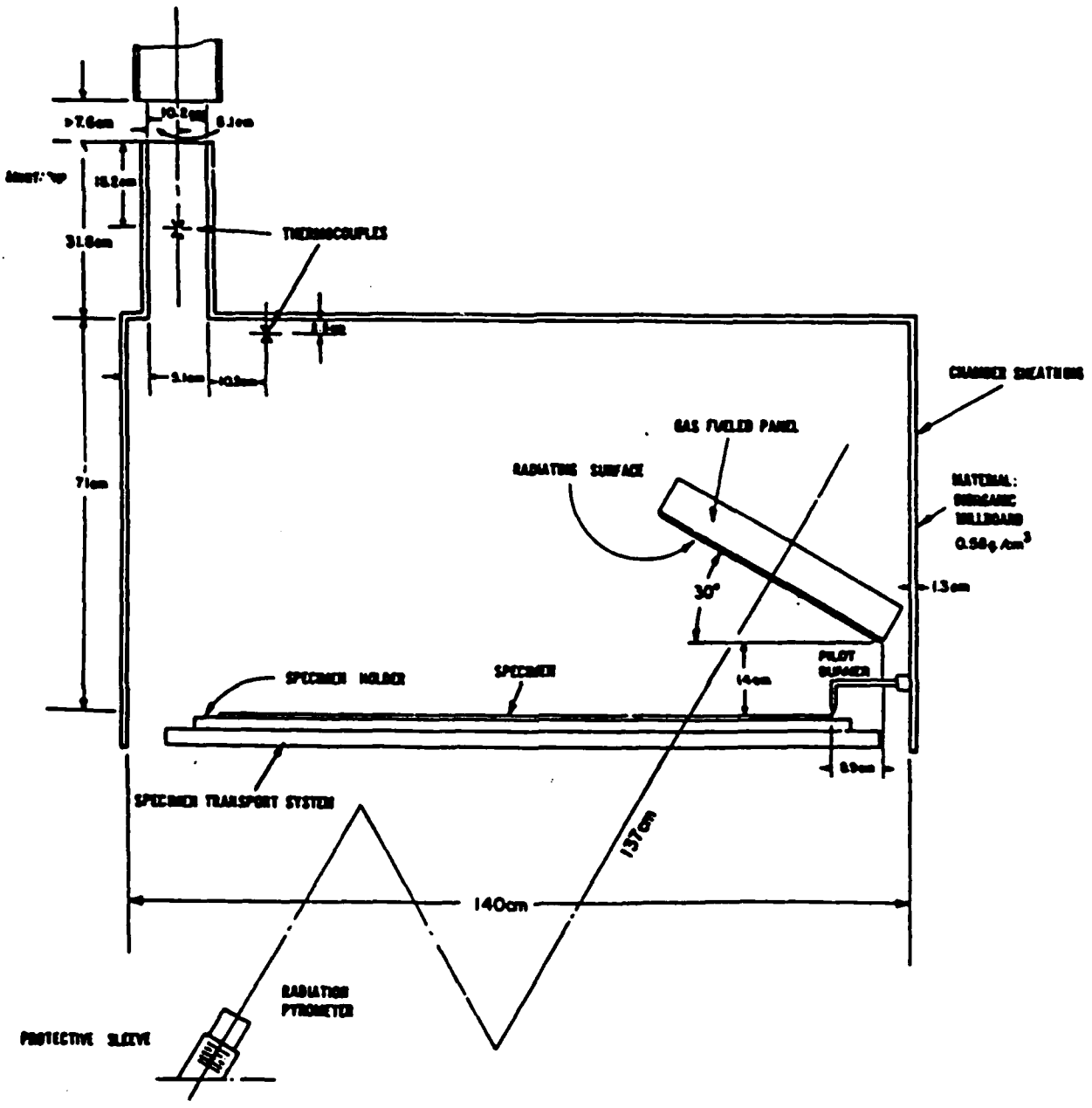

THERMOCOUPLES
CHAMBER SHEATHING
GAS FUELED PANEL
RADIATING SURFACE
MATERIAL:
INORGANIC
BOARD
30°
1.3cm
PILOT
BURNER
SPECIMEN HOLDER
SPECIMEN
14cm
71cm
SPECIMEN TRANSPORT SYSTEM
157cm
140cm
RADIATION
PYROMETER
PROTECTIVE SLEEVE

Fig. B-15

Quarter-Scale Room Fire Test

MIL-I-22023D

This method was developed in order to determine the relative flashover potential of wall lining materials.

The "room" is a 30 x 30 x 24 in. air tight box constructed of a ceramic insulation board. The vent is a 19.5 x 17 in. hole in the center of one wall. A pourous plate diffusion flame burner (3.5 x 3.5 x 3 in.) is used to line the inside of the test "room." The burner is positioned in one corner of the "room" and is calibrated to produce approximately 320 Btu. Thermocouples are located 1 in. and 3 in. below the top of the vent. Flashover is considered to occur if one of the interior thermocouples reaches 600°C or if one of the vent thermocouples reaches 500°C. Flashover should not occur within ten minutes to pass standard test.